Power Allocation in a QoS-Aware Cellular-based Vehicular Communication System

by

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PREFACE

The research contained in this dissertation was completed by Sello Leonard Mankge while based in the Discipline Electronic Engineering of School of Engineering of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Durban, South Africa.

The contents of this work have not been submitted in any form to another university and, except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate.

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Signed: Dr. Farzad Ghayoor

Date: 21-03-21

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DECLARATION 2: PUBLICATIONS

DETAILS OF CONTRIBUTION TO PUBLICATIONS that form part and/or include research presented in this dissertation:

Publication 1:

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ABSTRACT

The task of a driver assistance system is to monitor the surrounding environment of a vehicle and provide an appropriate response in the case of detecting any hazardous condition. Such operation requires real-time processing of a large amount of information, which is gathered by a variety of sensors. Vehicular communication in future vehicles can pave the way for designing highly efficient and cost-effective driver assistance systems based on collaborative and remote processing solutions. The main transmission links of vehicular communication systems are vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I). In this research, a cellular-based vehicular communication system is proposed where Device-to-device (D2D) communication links are considered for establishing V2V links, and cellular communication links are employed for V2I links.

D2D communication is one of the enablers of the next generation of cellular networks for improving spectrum and power utilization. D2D communication allows direct communication between user equipments within a cellular system. Nevertheless, implementing D2D communication should not defect nearby ongoing communication services. As a result, interference management is a significant aspect of designing D2D communication systems. Communication links in a cellular network are supposed to support a required level of data rates. The capacity of a communication channel is directly proportional to the energy of a transmitted signal, and in fact, achieving the desired level of Quality of Service (QoS) requires careful control of transmission power for all the radio sources within a system. Among different methods that are recommended for D2D communications, in-band D2D can offer better control over power transmission sources.

In an underlay in-band D2D communication system, D2D user equipments (DUEs) usually reuse the cellular uplink (UL) spectrum. In such a system, the level of interference can effectively be managed by controlling the level of power that is transmitted by user equipments. To effectively perform the interference management, knowledge of the channel state information is required. However, as a result of the distributed nature of DUEs, such information is not fully attainable in a practical D2D system. Therefore, statistical methods are

employed to find boundaries on the allocated transmission powers for achieving sufficient spectral efficiencies in V2I and V2V links without considering any prior knowledge on vehicles' locations or the channel state information. Furthermore, the concepts of massive multiple-input multiple-output and underlay D2D communication sharing the uplink spectrum of a cellular system are used to minimize the interference effect.

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LIST OF ABBREVIATIONS AND DESCRIPTIONS

ABBREVIATION	DESCRIPTION
3GPP	Third Generation Partnership Project
ADAS	Advanced Driver Assistance Systems
BS	Base Station
CSI	Channel State Information
CUE	Cellular User Equipment
D2D	Device-to-Device
DL	DownLink
DUE	Device-to-Device User Equipment
ISM	Industrial Scientific Medical
LoS	Line-of-Sight
LTE	Long-Term Evolution
MIMO	Multiple-Input Multiple-Output
ProSe	Proximity Services
QoS	Quality-of-Service
UE	User Equipment
UL	UpLink
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
VANET	Vehicular Ad hoc NETwork
WAVE	Wireless Access for Vehicular Environments

Chapter 1 : INTRODUCTION

1.1. Background

The desire to build autonomous vehicles and the need to increase the level of road safety has attracted much attention to the research and development of advanced driver assistance systems (ADAS). Such attention has also been paid to other related technologies, such as vehicular communications. A driver assistance system uses a variety of sensors for monitoring a vehicle's surroundings to detect hazardous conditions and so to act accordingly. The response of a driver assistance system, depending on the level of its complexity, can either be passive, such as giving a warning to the driver, or can be active by getting involved in controlling the vehicle. Although nowadays, most high-end vehicles are equipped with a form of a driver assistance system, deployment of such systems on a wide range of vehicles requires a thorough consideration of other factors such as the system's size, weight, and cost [1].

Vehicular communications and remote processing solutions can be considered as enablers for designing cost-effective ADAS in future vehicles. A cost-effective driver assistance system can operate based on a collaboration between nearby vehicles and the edge of a network. As a result, a collaborative driver assistance system requires an effective vehicular communication system to support sharing information among different entities. However, the overall system's performance would be highly dependent on the reliability of communication links.

Cellular-based vehicle-to-everything (V2X) communication links have been proposed by the Third Generation Partnership Project (3GPP) in Release 14 of the enhanced Long-Term Evolution (LTE) radio interface, which is known as LTE-Advanced (LTE-A). A collaborative driver assistance system, which operates based on LTE V2X links, can benefit from the already available and almost ubiquitous coverage of an LTE cellular network [2]. However, the requirements of V2X links, in the sense of data rate and required Quality-of-Service (QoS), for supporting different ADAS applications are yet needed to be identified.

The next generation of cellular networks, which is known as 5G, should support a higher data rate with a better QoS. Therefore, new techniques for improving cellular network capacity are required. Device-to-device (D2D) communications are one of the solutions for improving spectrum and power utilization in the next generation of cellular networks. The 3GPP proposed D2D in the Release 12 of LTE-A as Proximity Services (ProSe). In a D2D communication system, nearby mobile devices can communicate directly without their information traversing the cellular Base Station (BS) or the evolved NodeB (the radio part of an E-UMTS radio transmission site). As the distances between D2D user equipments (DUEs) are relatively short, D2D links can provide low-latency, high data-rate communications while consuming relatively less amount of energy.

Although ProSe is a public safety network feature, the specifications of D2D communications make it a suitable candidate for being used in a cellular-based vehicular communication system. The main links in vehicular communication systems are vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I), which can respectively be supported by D2D and Device-to-eNodeB links in a cellular-based V2X.

1.2. Problem Statement

In this research, a cellular-based vehicular communication system is considered. Vehicles in this system can be part of a V2V or V2I link without any limitation. The communication links between vehicles (V2V links) are formed based on underlay D2D communications. Recently, there has been much research on D2D-based vehicular communication systems to achieve the required QoS in the communication links. The majority of the efforts were on minimizing the effect of D2D communication on the nearby ongoing communication services by considering careful resource management.

Resource management includes controlling the utilized spectrum and the transmission powers to control and mitigate the interference effects. On the spectrum management part, the interference between cellular user equipments (CUEs) and DUEs can be cancelled by separating D2D and cellular communications spectra. However, in such systems, the allocated spectrum for D2D communications can be affected by other interference sources, which are not under the control of the cellular system. Alternatively, when the cellular spectrum is shared between

CUEs and DUEs, careful power allocation can be implemented to reduce the effect of interferences.

In this research, we will take an alternative approach for controlling the interference, which is by employing the concept of massive multiple-input multiple-output (MIMO) to minimise the interference effects of user-to-cellular links. This concept has not been considered in D2D-based vehicular communication systems. We then calculate the boundaries on the transmitted power in such a system to obtain the required throughputs for V2V and V2I links. The provided analysis are derived based on statistical averages. Therefore, prior knowledge of vehicle locations or the channel state information (CSI) is not required during calculations as the average of all possibilities is considered as the average performance. In summary, the problem is not to optimize power allocation to maximize the spectral of energy efficiency. Instead, it is to find the power boundaries to achieve the required QoS in communication links.

1.3. Aims and Objectives

The main aim of the research is to derive equations for calculating the minimum transmission power that provides the required spectral efficiency for both CUEs and DUEs, without considering any limitation on the spectrum sharing among devices. As the preference of D2D is for short-distance communications, we only consider D2D links between users that are in each other’s line-of-sight (LoS). The calculated boundaries have then been applied to a cellular-based vehicular communication system for calculating the transmission powers to achieve sufficient spectral efficiencies for V2I and V2V links.

The research objectives for this research are:

- Calculating the minimum transmission power that provides the required spectral efficiency for both CUEs and DUEs in a cellular network.

- Calculating boundaries on the V2I and V2V transmission links in a cellular-based vehicular communication system by considering the required spectral efficiencies.

1.4. Outline of Dissertation Structure

Chapter 2 Discusses an in-depth literature review with a focus on D2D communication systems, their advantages, and challenges. We then review the proposed methods for interference management in D2D communication systems. This follows by a review of the existing literature on D2D-based vehicular communication systems and interference management control techniques in such systems.

Chapter 3 Focuses on the mathematical concepts considered for wireless multipath propagation. We then present the concepts of Massive MIMO that will be the base of our analysis in future chapters.

Power allocation for a QoS-aware underlay D2D communication system is discussed in Chapter 4. We used the mathematical concepts that are covered in Chapter 3 to model the system and identify the power boundaries for obtaining the required channel throughputs.

Chapter 5 expands the model given in Chapter 4 to discuss the Power allocation for a D2D-enabled vehicular communication system. The main difference is the distribution of the users (vehicles) in such a system compared to the system covered in Chapter 4.

Chapter 6 focuses on the results and discussion. Numerical analyses have been used to demonstrate the effect of transmission power on the V2I and V2V spectral efficiencies.

Chapter 7 presents the conclusion drawn for this study.

Chapter 2 : LITERATURE REVIEW

2.1. Introduction

The demand for accessing information anytime and anywhere and the need for having a low delay, high data rate transmission links have led to a faster rate of advances in the development of cellular technologies. Nowadays, it is common for a user to have multiple devices simultaneously connected to the Internet through cellular and wireless networks. Also, the cellular networks' data-traffic is continuously on the rise, which creates pressure on the existing network resources. The fifth generation of cellular networks should support a communication system with data rates of 1 Gbps and, compared to its previous counterparts, should consume less power and offer better spectral and power efficiencies [3]. Moreover, the 5G should be capable of increasing the storage capacity and computational power of its connected devices by providing remote storage and distant computing capabilities [4]. As a result, employing new techniques for increasing energy and spectral efficiencies is required.

One solution for increasing the energy and spectral efficiencies of a cellular network is through densification, which is done by adding more network resources for reducing the size of the cells [5]. The employment of microcells, picocells, and femtocells in a cellular network are examples of such practice. Although densification will also decrease transmission delays, implementing smaller size cells requires additional infrastructure, which increases the cellular network's cost [6].

D2D communication is an alternative solution for improving spectrum and energy utilization in the next generation of cellular networks [7]. In D2D communication, nearby mobile devices, which are known as DUEs, communicate with one another without their data passing through a cellular BS. As the distances between DUEs are shorter than those between a cellular BS and its users, D2D communications can also reduce overall energy consumption in a cellular network [8] and enables D2D links to use less power for transmitting higher data-rates [9]. Another vital advantage of D2D communication is its capability to enhance coverage of a cellular network on the edges of a cell or in the areas where coverage is weak [10]. A BS can access out-of-coverage equipments through users that receive an adequate level of signal power.

All the specifications mentioned above make D2D communication an essential player in the 5G cellular network and also, different applications can be considered based on the D2D communications concept. Examples of such applications are in sharing large volume contents such as videos and pictures [11], disaster relief [12], gaming [13], and vehicular communications [14]. The D2D communications is also a favourable technology in designing cost-effective ADAS applications for future vehicles [15].

2.2. D2D Communications Challenges

Despite D2D communications' numerous advantages, many issues such as discovery methods, mode selection, resource management, mobility, and security are still needed to be addressed before D2D communications can be fully implemented. The first requirement to establish a D2D communication network is that a device should discover other potential candidates for setting up a direct D2D connection. For this purpose, DUEs should share beacon signals containing information such as a device's ID, location, and channel state information [16]. The potential D2D receivers can then use this acquired information to evaluate the possibility of pairing with one another. The discovery procedure can be done with the help of a central entity, such as a BS (centralized discovery) [17], or can be done among user equipments themselves (distributed discovery) [18].

The next challenge in D2D communications is known as mode selection, which identifies the way that DUEs can communicate with each other. In summary, mode selection deals with the allocation of the frequency spectrum for D2D communication links in a cellular network [19] and also identifies the number of DUEs, which can be involved in establishing a D2D communication network [20]. Pure cellular, partial cellular, underlay/overlay D2D, and single/multiple hop(s) are examples of modes that can be selected for a D2D communication system. The concept of D2D communication is nothing new, and it has existed in different forms of technologies since the earlier generations of mobile devices. Direct Wi-Fi and Bluetooth connections are among these technologies that are implemented over the unlicensed spectrum. D2D communication, as part of a licensed spectrum, was first proposed in [21] to support multi-hop relays. Other studies showed that D2D communications have the potential to improve, both, spectral and energy efficiency of a cellular network [22]. Nevertheless, it was only in 2012 that the 3GPP proposed D2D communications in the Release 12 of LTE-A as ProSe, which is a public safety network feature [23].

D2D communications, as is shown in Figure 2.1, is categorized based on its operational frequency spectrum into in-band and out-band D2D systems. In the in-band D2D, the communication between D2D devices occurs at the same spectrum as the cellular communication, and in the case of out-band D2D, an unlicensed spectrum is considered for the D2D links.

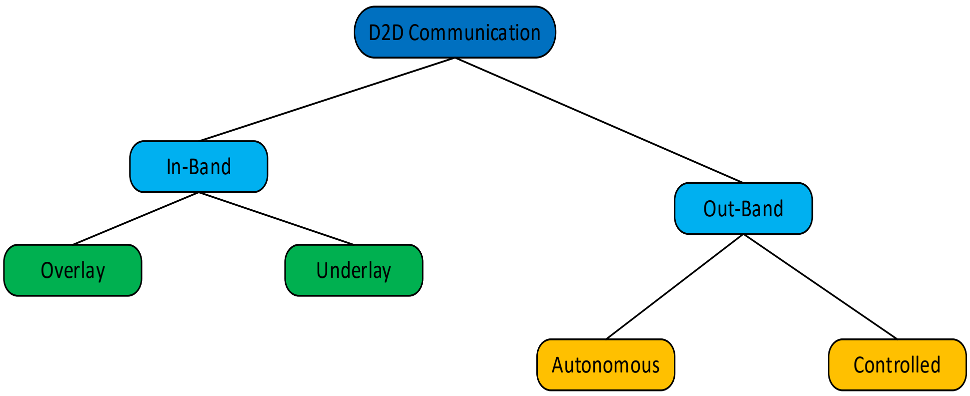

Figure 2.1. D2D communications classification [24]

The in-band D2D communication is classified as underlay and overlay [25]. In the in-band underlay scheme, DUEs competitively use the complete spectrum allocated to cellular communications. This means the D2D communication links reuse the dedicated resource blocks assigned to the CUEs in a direct communication mode. The in-band underlay D2D communication can improve the spectral efficiency of a cellular network [26]. In the overlay D2D communication system, only a portion of the cellular spectrum is allocated for D2D communication [27]. The portion that is allocated to the D2D communication cannot be used by cellular links. Therefore, the effect of cross-interference will be reduced.

The out-band D2D communication uses the licensed cellular spectrum for CUEs communications and an unlicensed spectrum, which are mostly Industrial Scientific Medical (ISM) bands, for D2D links [7]. Bluetooth and Wi-Fi are examples of technologies, which operate over the ISM band. In the previous generations of cellular networks, the users of such systems have to set up each D2D link manually. However, a better user experience can be obtained if a BS and devices can automatically handle D2D parings. Nevertheless, the main challenge of the out-band D2D is the need to encode and decode data packets between D2D and cellular networks, as an alternative radio interface with a different protocol is used for D2D communication. The out-band D2D communication is categorized into controlled and autonomous methods. In the controlled out-band D2D communication, a BS coordinates radio interfaces between devices, and DUEs have a pre-allocation on their spectrum resources. The BS can then meet the QoS requirement by prioritizing transmission for a particular user. The major setback of this method is the long delays, which are experienced due to the increase in network size that also increase the signalling overhead and reduce the performance of a network. To reduce the BS workload of an out-band D2D communication system, control of D2D communications can be transferred to the users' devices. This method of D2D communication is known as autonomous out-band D2D. The autonomous out-band is especially attractive for mobile service providers and operators since the devices in the D2D network control resource allocations among themselves, and hence the signalling overhead would be reduced. Moreover, the autonomous out-band eases the deployment of the BS as the network traffic management would be offloaded to the mobile devices.

Although reusing the available bandwidth in an underlay D2D communication system can significantly improve the spectrum efficiency and increase the overall capacity of the network [28], it requires careful consideration in allocating the available resources. This brings up the next challenge in D2D communications, which is known as resource management. Resource management deals with the efficient ways of managing resources to mitigate interference, save power and maximize capacity. The available resources that can be controlled are the transmitted power and the allocated spectrum. With the addition of D2D users to a cellular network, spectrum resource allocation is needed to be carefully managed for achieving the required level of QoS [29]. Power control is another aspect of resource management. This includes controlling transmission power for both uplink (UL) and downlink (DL) of a cellular network as well as the transmission power of D2D communication transmitters.

Mobility management is also an essential aspect of D2D communications since DUEs may change their location while communicating with each other. As a result, their connectivity and communication can get interrupted. Mobility management consists of two operations, namely the location management and handoff management [30]. Location management enables the network to track the attachment points of mobile terminals between consecutive communications as they roam around a network [31]. Handoff management enables a network to maintain users' connections as a user moves from one attachment point to another.

Finally, D2D communication is vulnerable to the same security and privacy threats as cellular and ad-hoc wireless networks. Security threats can affect authentication, confidentiality, integrity, and availability of a network [32]. D2D communication requires efficient security solutions to enable secure, private, and trusted data exchange between devices. The security problem is needed to be dealt with in the concept of proximity-based direct communication and without any assistance from a cellular network.

In this research, we consider an underlaid D2D communication system, and the focus is on resource management to achieve a certain level of QoS in the system. The main aspect of resource management is to control the interference caused by D2D links. Therefore, in the next section, we will review the interference management techniques in D2D communication systems.

2.3. Interference Management in D2D Communication Systems

By integrating DUEs into a cellular network, the cellular architecture evolves into a two-tier cellular system, known as the macro and device tier. The macro tier includes the cellular communication between BS and CUEs, and the device tier involves D2D communications [33]. The system's design should be such that the implementation of the device tier does not affect the ongoing macro-tier communication services. The future cellular network will have to support various devices, including many low-power transmitters, which are part of its D2D communication network. Therefore, interference management in the future cellular network is a non-trivial task [34]. The two main leverages that can be used to mitigate the effect of interferences are controlling the spectrum and power resources.

The cross-interferences between CUEs and DUEs can be alleviated by separating the operational spectrum of cellular and D2D communication links. The ultimate separation can be achieved in the out-band D2D, where separate bands are considered for D2D and cellular communications. However, in the out-band D2D, a cellular network does not have any control over other radio sources operating over the unlicensed spectrum. Therefore, such resources can cause uncontrollable interferences to the ongoing D2D communication links and reduce QoS. As a result, achieving the required QoS cannot be guaranteed in an out-band D2D communication system [35].

On the other hand, QoS management is feasible if all transmission sources become controllable within the same system. In the in-band D2D, either the UL or DL cellular spectrum is shared among D2D communication links. This makes the BS and cellular mobile devices the only transmitting sources, and so the interference level can effectively be managed within the cellular system. However, as a result of sharing a frequency spectrum, such a system is prone to intrasystem interference. The interference of the in-band D2D communication can be reduced by allocating a portion of the cellular spectrum specifically for D2D communication. The limitation of this method, which is known as the overlay D2D, occurs when the allocated cellular spectrum for D2D communications is used inefficiently, which leads to reduced resource utilization and spectrum deficiency [36].

The UL spectrum is always under-utilized, and there would be enough bandwidth to be reused for D2D links without affecting the performance of the cellular system. As a result, sharing the UL resources is the preferable choice in the underlay D2D communication systems [37]. However, reusing spectrum resources by the D2D links may cause significant degradation to the system performance. In the next section, the research that has been done on interference management in the underlaid communication systems will be reviewed.

2.3.1. Interference Management in Underlaid D2D Communication Systems

The available resource blocks in an underlaid D2D communication system are simultaneously used by cellular and D2D users. Therefore, the effect of interference caused by D2D links on the cellular links should be managed through techniques other than spectrum and time separation. Such techniques include power management and spatial-division multiplexing. The most common solution for controlling interference in an underlay D2D system is by restricting the transmission power between D2D links [38]. Power management in a UL underlaid D2D communication system should automatically be done by adjusting power levels in UEs during UL transmissions.

Due to the increasing demand for achieving higher throughputs in cellular networks, optimization of the power and spectrum utilization is a necessity for the overall improvement of the system capacity. Although increasing power in the transmitter would directly result in a capacity increase; it indirectly increases the interference level between devices that share the same spectrum. The power control algorithms can be employed in the context of resource management, which means combining the power control with mode selection to achieve a required system performance [39, 40].

The power control algorithms are categorized into centralized and distributed methods. In centralized algorithms, a BS controls and makes the necessary decisions for allocating power and spectrum resources. In contrast, in distributed algorithms, each mobile device decides independently on selecting the level of transmission power. Parameters such as maximum transmission power, CSI, number of resource blocks and received power per resource block are considered in different power control algorithms. It is common to implement power allocation in a centralized manner. However, the centralized schemes may not be suitable in a large network as they involve a high level of complexity. Instead, distributed power allocation techniques are preferable in such networks.

It was shown in [41] that a centralized power allocation method could maximize the sum rate of D2D links and guarantee reliable cellular communications. However, it requires knowledge of the global CSI at the BS, which increases the system’s overhead. On the other hand, a distributed method that maximizes the D2D links’ sum rate would not be able to guarantee the required QoS of the cellular links. Authors in [42] showed that in a centralized method, the maximum throughput could be achieved if a BS can control the mode of communication in D2D links. In other words, by allowing a BS to select the communication spectrum in D2D links, higher throughput can be obtained. However, in such a system, all devices should be capable of switching between the different operational spectrum.

A combination of spectrum and power allocation has been considered in [43] to maximize the overall network throughput while maintaining the required QoS. In this method, a BS only allows admission of D2D communications if the established D2D link has the potential to achieve the minimum QoS based on the value of the signal-to-interference-plus-noise ratio (SINR) and does not interfere with the ongoing cellular links spectrum. Therefore, a BS should continuously monitor the power and spectrum allocation throughout the network, which increases its workload. [44] proposed that the power control mechanism offload the monitoring workload to the D2D users. They assumed a system wherein a BS constantly transmits the maximum allowed power to the devices so that their transmission power does not exceed a certain threshold during D2D communications. Moreover, D2D users were only allowed to communicate during the uplink frame to reduce the interference effects on the cellular users.

Authors in [45] modelled an underlaid D2D communication system where the uplink spectrum could be used by the cellular and D2D users simultaneously and without any constraint. They then optimized the system based on the power transmitted by the D2D users to achieve the maximum rate and energy efficiency for the D2D links. However, no QoS for the communication links were considered. [46] modelled an underlay D2D system, where each D2D link can utilize multiple resource blocks from different cellular users. Based on this assumption, they proposed an optimum power allocation scheme to maximize the cell sum rate and D2D throughputs. In their model, the interference from the neighbouring cells was also considered. However, only the QoS for the cellular links were guaranteed, and the D2D links should transmit the maximum power accordingly. The utilization of resource blocks from multiple cellular users by a D2D pair is also considered in [47]. The main objective of this work was to allocate the power such that the QoS on both cellular and D2D links can be guaranteed. The system was modelled based on the statistical CSI, and multiple optimal and suboptimal power allocation methods were proposed. [48] considered the energy-efficiency and the QoS for both D2D and cellular links. In their work, they first maximized the energy efficiency of

D2D pairs one by one according to the required QoS, and then a spectrum allocation was done between the cellular and D2D users to minimize the interference. However, the complexity of this proposed algorithm is very high, which imposes a high workload on the BS. In [49], a more realistic system based on randomized D2D users' locations where considered. For such a system, power control and channel allocation methods based on the distances between D2D and cellular users were proposed, which resulted in decreasing the density of active D2D users sharing the same resources.

Recently, [50] studied the Simultaneous Wireless Information and Power Transfer (SWIPT) in D2D communication systems. Under this assumption, the interference can be exploited as beneficial signals to devices for energy harvesting. Therefore, the power allocation problem for achieving energy-efficiency can be treated differently as the transmitted power can be harvested by the other users.

Spatial-division multiplexing has also been investigated to reduce the interference level in underlaid D2D communication systems. Massive MIMO (Multiple-input Multiple-output), which is also known as large-scale antenna systems (LSAS), has been recognized as a promising technology for achieving higher data capacity in the next generation of mobile-cellular networks. Massive MIMO is mainly used for spatial-division multiplexing, where different data streams occupy the same frequencies and times. The concept of massive MIMO and spatial-division multiplexing can be used to develop an efficient multiuser MIMO (MU-MIMO) communication system.

In contrast to single-user or point-to-point MIMO, an MU-MIMO cellular communication system consists of a BS with multiple antennas for simultaneously servicing a set of multiple or single antenna users [51]. All users in such a system share multiplexing gains. An independently controllable array of antennas enables MU-MIMO systems to carry data on focused beams. In a cluttered propagation environment, data streams can be received from different directions simultaneously. A well-designed MU-MIMO system can reinforce data streams constructively where desired and interfere destructively where unwanted.

An MU-MIMO system requires knowing the frequency response of every user's propagation channel. Such information is obtained based on measurements rather than assuming channel characteristics. An LS-MIMO system uses a known training signal to estimate the frequency response of both UL and DL channels. Once the channels have been estimated, the CSI has to be utilized promptly before users' channel conditions significantly change. Hence, there is only a limited amount of time available for training. Both training and data transmission takes place in a time slot, which its duration is chosen so that no user can move more than a fraction of a wavelength during that time. CSI is used for both precoding in downlink and decoding in the uplink. Precoding includes mapping of data streams to drive each antenna for beamforming. An increasing number of antennas help to form beams, which can be focused more selectively on a particular user [52]. Decoding consists of designing a matched filter for the uplink data transmission.

Received symbols in MIMO communication systems are subjected to impurities, such as interference and random noise. These symbols can be detected separately or jointly. A joint detection has a better performance compared to a separate detection as characteristics of other symbols will be taken into account for detecting each symbol [53]. Co-channel interference (CCI) is an essential aspect of MIMO communication systems, which can offer essential benefits to MIMO communication detection techniques. Nevertheless, CCI enforces some limitations as well. For instance, CCI problem-solving algorithms have high computational complexity for optimum MIMO detection. Such complexities increase with the number of decision variables. However, with the advancement of computing power over the years, such limitations may no longer be regarded as a hold-up for practical applications. CCI's main feature is the overlapping of multiple transmissions. Such overlapping can take place over a frequency band or a time slot.

The interplay between MIMO systems and D2D communications can be employed to control the level of interference in an underlaid system as the D2D communication links cause continuous interference on the ongoing cellular communication transmission. It is shown in [54] that when the number of antennas at a BS is sufficiently larger than the number of serviced users, the users' channels can be designed to be orthogonal. Therefore, by employing a large array of antennas, the interference between D2D and cellular communications can be nullified. Such a technique allows close to zero interference on cellular links from underlaid D2D communication users. Although large arrays of antennas at a BS can assist in controlling the effect of interferences, by scaling the number of active users, D2D communication still contributes to the overall interferences of a cellular network through reusing radio resources. Therefore, to protect D2D links, the number of active D2D users has to be limited. The majority of existing research on D2D communication is based on single-antenna users, while research on large antenna arrays has just begun. However, the estimation of CSI in a cellular system with an underlaid D2D communication will be less accurate. This is a result of CCI presence during the channel estimation process and is one of the trade-offs in supporting D2D communication in a massive MIMO communication system.

The work of [55] introduced a power control solution in an underlaid D2D communication system benefiting from Massive MIMO to control the interference without a need to obtain the global CSI of the system. They showed that adding more antennas to the massive MIMO system can improve the spectral and energy efficiency of the whole system. However, a critical factor in such a system is the maximum number of D2D devices that can simultaneously be operational in the network. [56] studied the feasibility of pilot reuse by D2D users in an underlaid massive MIMO system to reduce the signalling overhead during CSI estimation. They introduced a pilot scheduling and power control algorithm in D2D devices to mitigate their effects on the cellular network channel estimation. Moreover, a power control algorithm has been proposed to maximize spectral efficiency while obtaining the required level of QoS. In [57], a power control method for a massive MIMO system with underlaid D2D communication links is proposed that jointly optimizes the power for both data and pilot signals.

2.4. Application of D2D Communications in Vehicular Communications

IEEE 802.11p [23] and cellular-based V2X communications are the technologies that are considered for vehicular communications. Until 2016, IEEE 802.11p, which is part of wireless access for vehicular environments (WAVE) protocol [58], was the only accepted standard for vehicular ad hoc networks (VANETs) [59]. However, there are two types of delays that are associated with the WAVE. One is as a result of the carrier sense multiple access with collision avoidance (CSMA/CA) mechanism used by the IEEE 802.11p protocol, and the other is due to the WAVE limited transmission range that is typically 100-200m [60]. Moreover, WAVE can only support a maximum of 800 Bytes in each transmission that happens every 100ms, and therefore, cannot guarantee the required QoS and access delay for many types of ADAS applications [61].

Cellular-based V2X was proposed by the 3GPP in Release 14 of LTE (LTE-V2V) [62] and has the potential to offer the required performances needed by ADAS applications [2, 61-64]. Moreover, it can benefit from the already available and almost ubiquitous coverage of cellular LTE systems. Fast channel variation and high mobility of users are parts of a vehicular communication environment. However, such environmental challenges can be addressed by employing direct and short-distance communication links. D2D communications enable nearby mobile devices to communicate with one another without their data traversing the core network or cellular BS and usually takes place over short distances. As a result, it can provide a low-latency, high data-rate transmission while spending a relatively small amount of power [65]. Such specifications are essential for an efficient vehicular communication system and make D2D communications suitable candidates for establishing V2V links between nearby vehicles [66].

The main links in vehicular communications are V2V and V2I, which are respectively supported by D2D and Device-to-BS links in a cellular-based V2X. It was shown in [67] that a better delay performance could be achieved by introducing overlay-D2D to a WAVE-based VANET. However, the limitation of overlay D2D occurs when the allocated cellular spectrum for D2D communication is inefficiently used, which leads to reduced resource utilization and spectrum deficiency. The spectrum deficiency problem can be mitigated by employing underlay D2D under careful resource management. In the next section, we review the works that have been done on employing underlaid D2D systems in vehicular communications. The main aspect of this research is on achieving the required QoS in communication links while mitigating the interference effects.

2.4.1. Interference Management in D2D-based Vehicular Communications

A centralized resource allocation for V2I and V2V connections in an underlay D2D communication system can be determined by a BS, assuming it poses the capability of choosing the best resource sharing scheme for V2V and cellular connections. V2V and V2I communication links are allowed to share the same resources for their individual data transmission. Such resource management is very crucial. D2D communication techniques for supporting V2V links require a more detailed study, as the rapid change of channel state has to be taken into account in radio resource management. A feasibility analysis has been carried out in [68] to evaluate the applicability of the D2D underlay resource allocation for the support of joint V2V and V2I connections, and it was shown that D2D-assisted vehicle underlay communication can surpass traditional V2V techniques.

It was shown in [69] that the overall network throughput is not necessarily enhanced by employing more D2D transmissions between vehicles in an urban environment. This is because the SINR in the underlay D2D systems is sensitive to the number of D2D links. A vehicular communication network based on an underlay D2D communication system was envisaged in [70], where each D2D link could only share a spectrum with one cellular link at a time. Based on this assumption, different resource allocation methods were proposed to maximize the throughput of V2I links while maintaining the minimum QoS for V2V. [71] proposed a cluster-based system wherein multiple V2V links could share spectrum with a cellular link. The objective of this research was to allocate power for maximizing the sum rate of cellular users while satisfying the latency and reliability requirements of V2V links according to the vehicular communications requirements proposed by the European union METIS project [72]. In their method, both clusterings of V2V users and power allocation processes should be done at the BS. Power allocation based on machine learning techniques has been suggested in [73] for D2D-based V2V communications. This work aimed to improve the energy efficiency of the overall system while maintaining the QoS in V2V links. It was shown that after the training phase, the amount of the required computation would be small enough to be performed on the users' equipments. [74, 75] have optimized power allocation for D2D-based vehicular communication systems to meet the required QoS in V2V and V2I links considering different latencies related to the packets' transmission. They studied the probability of packet loss in the reliability of the system. The power optimization in their works aimed to achieve the maximum sum rate. The sharing of the spectrum by V2V users was studied in [76] by taking data security into account. They have also optimized their system to achieve the maximum sum rate. In [77], a suboptimal power allocation algorithm based on the game theory was proposed to maximize the minimum throughput of V2V links under the constraint of a minimum value for V2I links. Xiao et al. [78] considered energy harvesting in their system and, based on that, optimized the power allocation to obtain the maximum energy efficiency. Moreover, in contrast to other studies, they assumed an underlay D2D system by sharing the DL spectrum.

The main assumption in the abovementioned papers was that the slowly varying CSI of all links are perfectly known by the system and can be used in the resource allocation algorithms. Liu et al. [79] made a more realistic assumption, which was the knowledge of delayed CSI by the users. Based on this assumption, they proposed an optimized power allocation scheme to maximize the system's sum rate.

2.5. D2D Communications Performance Evaluation

Different objectives, such as power efficiency and spectral efficiency, have been considered for optimizing the performance of UL D2D underlay cellular systems. In [80], an underlay D2D cellular system with a fixed number of mobile devices was considered, and it was shown that by employing D2D, the amount of power consumption of the whole system was reduced. The authors of [81] considered a single-cell scenario that the BS is aware of the CSI and can control DUEs' transmit powers. They showed that in a system with one CUE and a pair of DUEs, the sum rate can be increased by up to 45%, provided that the system knows the interference of each link as a priori information.

QoS-aware communication systems are of great importance in situations that communication links are supposed to provide minimum transmission rates. [43] proposed a power allocation scheme to obtain a QoS-aware D2D system. However, the method was only limited to a situation that a pair of DUEs at its most shares spectrum with only one CUE. Authors in [44] suggested that DUEs should be able to adjust their transmission power level according to the required QoS by other CUEs and DUEs in the system. However, their work is based on the assumption that DUEs know the location and CSI of CUEs, which is either not feasible in a real system or imposes a high overhead signalling to the system.

2.6. Summary

In this chapter, the most recent publications on D2D communication and cellular-based vehicular communications were reviewed. D2D communications are considered as a solution for improving power and spectrum utilization in the next generation of cellular networks. D2D links use less power to transmit higher data rates with fewer delays between user equipments in a cellular system. However, with the addition of D2D users to a cellular network, spectrum and power resources are needed to be carefully managed for achieving the required level of QoS. D2D communications are also suitable candidates for establishing V2V links between nearby vehicles. Studies have shown that D2D-assisted vehicular communication can surpass traditional V2V techniques. The next chapter discusses the mathematical concepts that are used for modelling D2D communication systems.

CHAPTER 3 : MATHEMATICAL MODELS

3.1. Introduction

In this chapter, we provide the mathematical concepts that will be used in the following chapters to model our proposed solution for power allocation in a D2D-based vehicular communication system. We first cover the cellular system that has been considered in our analysis. This follows by the model of the wireless channel. Finally, we present the mathematical formula for the LS-MIMO, which will be used in our considered underlaid D2D system.

3.2. Cellular Systems

A cellular system is an infrastructure-based wireless network, which operates based on the concept of reusing spectrum for spatially separated locations, known as a cell. A base-station, or an access point, is located at the centre of a cell and provides a centralized control mechanism for dynamic allocation of resources, controlling power, scheduling transmissions and handoff. Reusing of the spectrum is based on the fact that a base station's propagation power falls off with the distance, and therefore, in an ideal scenario, an area can be divided into non-overlapping cells. It is typical to consider a cellular network with non-overlapping hexagonal cells, where each cell neighbouring six other cells. Although in practical situations, circular shape cells are closer to the wave propagation model.

A base station uses the DL channel to send information to cellular users, and cellular users use the UL channel to communicate with a base station. In a cellular system, the UL and DL channels are separated into orthogonal signalling dimensions using time-division duplexing (TDD) and frequency-division duplexing (FDD). As, both, UL and DL channels have to be shared among different users in a cell, using multiple access techniques are required to divide the available signalling dimensions among the cellular users. Time-division multiple access (TDMA), Frequency-division multiple access (FDMA), Code-division multiple access

(CDMA), Space-division multiple access (SDMA) and their hybrid combination are different multiple access methods used in cellular systems.

In the 5G cellular system, the length of each radio frame is 10 ms. Each frame is then divided into 10 subframes of length 1 ms. Subframes are formed by the number of slots, which varies according to the numerology used for the 5G, and each slot contains 14 OFDM symbols. The length of each slot is dependent on the 5G configuration and is equal to $\Delta \mathrm{T} = \frac{1}{2^{\mu}}$ ms, where $\mu = 0,1, \dots ,4$ and represents the employed numerology. The 5G has the flexibility of assigning a consecutive number of symbols in each slot as DL, UL or Flexible. The combination of DL, UL and Flexible symbols in a slot is defined by the slot format. A resource block (RB) in the 5G cellular system is made up of one slot in the time domain and 12 sub-carrier in the frequency domain. The sub-carrier spacing is also dependent on the 5G configuration and is equal to $\Delta f = 2^{\mu} \times 15$ kHz. It is important to note that numerology 4 does not support data transmission and is only used for synchronization. The maximum supported bandwidth for $\mu = 0$ is 40 MHz, which can contain 270 RBs, and this for $\mu = 3$ is 400 MHz that supports 264 RBs. In the LTE cellular system, the number of slots per subframe is 2. So the length of each slot is 0.5 ms. The LTE bandwidth varies from 1.4 to 20 MHz, but the subcarrier spacing is always 15 KHz. Therefore, a 1.4 MHz LTE system contains 6 RBs and this for a 20 MHz is 100 RBs.

A cellular has to cope with interference from within a cell, known as intracell interference, as well as the interference from outside a cell, which is from neighbouring cells, referred to as co-channel or intercell interference. The co-channel interference is a result of channel reuse by the other cells, and the intracell interference is due to non-orthogonal channelization or the multipath effect and lack of effective synchronization. Nevertheless, in an underlaid D2D communication system, which will be explained in the coming sections, the co-channel interference is also considered as part of intracell interference as the spectrum resources are used by multiple D2D and cellular devices, simultaneously.

Both types of interferences would affect the amount of SINR at the receiver, which is calculated as

$$SINR = \frac{P_r}{N + P_I} \tag{3.1}$$

where P_r is the received signal power, N is the noise power and P_I is the received power caused by both intercell and intracell interference.

The performance of a cellular system depends on SINR, and mitigating interference is a key factor for improving the performance of a cellular system. Intercell interference can be controlled by increasing the distance between the cells using the same channels. On the other hand, intracell interference can be managed by spectral, temporal and spatial resource allocation, such as employing orthogonal signalling dimensions for multiple access as well as by careful power control mechanisms.

3.3. The Model of a Wireless Channel

Wireless multipath propagation is a phenomenon of a transmitted signal reaching a receiver by more than one propagation path. In an ideal broadcasting wireless system, the transmitted signal radiates in all directions from the transmitter to an infinite distance with no degradation. However, different types of attenuations will affect transmitted signals in practical systems. Such effects in a mobile radio propagation system are described in terms of large-scale and small-scale effects. Large-scale effects include the variation of the mean received signal strength over large distances, and small-scale effects involve the variation of the mean received signal strength over small distances relative to the signal wavelength. In addition to the small-scale and large-scale effects, the transmitted signals in a wireless medium will also be corrupted by random fluctuations of electrons within the air, which is known as noise. Channel models can also describe based on the empirical models and according to the measurements of the received signals.

The most common impairments factors for multipath degradation propagation are reflections, diffractions, and scattering from terrestrial environments such as buildings, mountains, trees, etc. Reflections occur when a radio signal collides with a massive object with large dimensions compared to the wavelength of the propagating signal. Diffractions happen when a surface obstructs the radio propagation path between the transmitter and the receiver with sharp edges. Scattering occurs when the radio signal travels through a medium consisting of objects with dimensions that are small compared to the signal wavelength. Generally, the most critical large-scale impairments in a mobile channel are path loss and shadowing. Fading, on the other hand, is due to small-scale effects.

3.3.1. Path Loss and Shadowing

Free-space transmission between a transmitting antenna and a receiving antenna introduces a reduction in the transmitted signal power density. Path loss models are used to predict the transferred power and quantify the difference between the transmitted power, P_t, and received power, P_r. Numerous parameters are affecting the path loss of a mobile radio propagation beam. Base station antenna height, mobile antenna height and operating frequency are among such parameters, but overall the path loss is equal to

$$P_{L\,\mathrm{dB}} = 10 \log \frac{P_t}{P_r} \tag{3.2}$$

An accurate path loss model can be achieved from empirical models. However, a simple model for path loss can be useful to analyse various system designs. The simplified path loss model is given in [82] by

$$P_{L\,\mathrm{dB}} = -A_{\mathrm{dB}} + 10\alpha \log d \tag{3.3}$$

where A_{dB} is a constant negative number depending on the antenna characteristics and α is known as the path loss exponent. Both of these values can be approximated from the empirical measurements. d is the distance between the transmitter and the receiver.

Shadowing is experienced due to the significant obstruction of the electromagnetic signal between the transmitter and the receiver. The shadowing effect experienced by the received signal power due to large buildings, trees, and hills between the transmitter and receiver propagation path. A log-normal model is a widely used model for the shadowing affected by a large number of shadowing objects. According to [82], in this model, ${P_t}/{P_r}$ can be expressed as a random number with the probability density function (PDF) of

$$f(\psi_{\mathrm{dB}}) = \frac{1}{\sqrt{2\pi}\sigma_{\psi_{\mathrm{dB}}}} e^{\frac{-\left(\psi_{\mathrm{dB}}-\mu_{\psi_{\mathrm{dB}}}\right)^2}{2\sigma^2_{\psi_{\mathrm{dB}}}}} \tag{3.4}$$

Where $\psi_{\mathrm{dB}}$is the shadowing loss in dB and $\sigma_{\psi_{\mathrm{dB}}}$ and $\mu_{\psi_{\mathrm{dB}}}$ are the standard deviation and mean of ψ_{dB} log-normal random variable.

The path loss and shadowing models can be combined to model the power falloff versus distance. This combined model is given in [82] as

$$\left(\frac{P_r}{P_t}\right)_{\mathrm{dB}} = A_{\mathrm{dB}} - 10\alpha \log d - \psi_{\mathrm{dB}} \tag{3.5}$$

where ψ_{dB} is a zero-mean Gaussian random variable with the variance of $\sigma^2_{\psi_{\mathrm{dB}}}$. Therefore,

$$\frac{P_r}{P_t} = \frac{A}{\psi} d^{-\alpha} = A\beta d^{-\alpha} \tag{3.6}$$

3.3.2. Small-Scale Fading Model

When a signal is affected by a large number of multipath components, statistical models must be used to model the channel. Multipath propagation leads to multipath fading, which exhibits randomness in the received signal strength, phase, and angle of arrival. As a result, the receiver sees the superposition of multiple transmitted copies, each of which experiencing attenuation, phase shift, and delay. According to [82], the baseband equivalent of a received signal through a fading channel is

$$r_l(t) = \int_{-\infty}^{\infty} h(\tau, t) s_l(t-\tau) e^{-j2\pi f_c \tau}\, d\tau \tag{3.7}$$

where f_c is the carrier frequency of the transmitted signal.

As can be seen, the signal is affected by the channel time spread, τ, and attenuation factor, h, which both are a function of time, t. Depending on the motion between a transmitter and a receiver, a multipath channel may be considered time-variant or time-invariant. The Doppler spread, B_d, characterizes the time variation of a fading channel. In mobile communication, B_d is specified by the speed of a mobile receiver as

$$B_d = \frac{f_c}{c} v \tag{3.8}$$

where v (m/s) is the speed of the mobile, c is the speed of light (3e8 m/s) and f_c is the transmission carrier frequency. $B_d = 0$ corresponds to a static channel.

For a transmitted signal with a transmission rate of $1/T$ signal per second, the channel is considered as a slow-fading channel if $1/T \gg B_d$, which means for at least one signalling interval, the channel attenuation and phase shift are essentially fixed. Otherwise, the channel is called fast-fading. Moreover, the spread of a channel, τ, is characterised by the maximum path delay, T_m. A channel is considered as frequency-selective if $T \ll T_m$ and flat or frequency-nonselective if $T \gg T_m$.

For a flat, slow-fading channel, when a large number of reflections occur at the receiver, based on the central limit theorem, the multipath channel can statistically be modelled as a complex Gaussian random variable. For such a channel, each transmitted signal is corrupted by attenuation and a phase shift. If no line-of-sight (LoS) path exists between transmitter and receiver, the attenuation is modelled as a Rayleigh random variable, and if an LoS path exists, the attenuation has a Rician distribution. The phase shift has a uniform distribution in the range of $(0,2\pi)$. For an attenuation in the Rayleigh channel, the Probability Density Function (PDF) of $|h|$ is

$$P(|h|) = \frac{2|h|}{\Omega} e^{-\frac{|\mathrm{h}|^2}{\Omega}} \tag{3.9}$$

where $E\{|\mathrm{h}|^2\} = \Omega$ is the mean power of the received signal with the transmitted power of 1 watt, the PDF of the envelope of a received signal in a Rayleigh fading channel with $\Omega = 1$ is shown in Figure 3.1. The channel is in adverse condition with a probability of 0.6325.

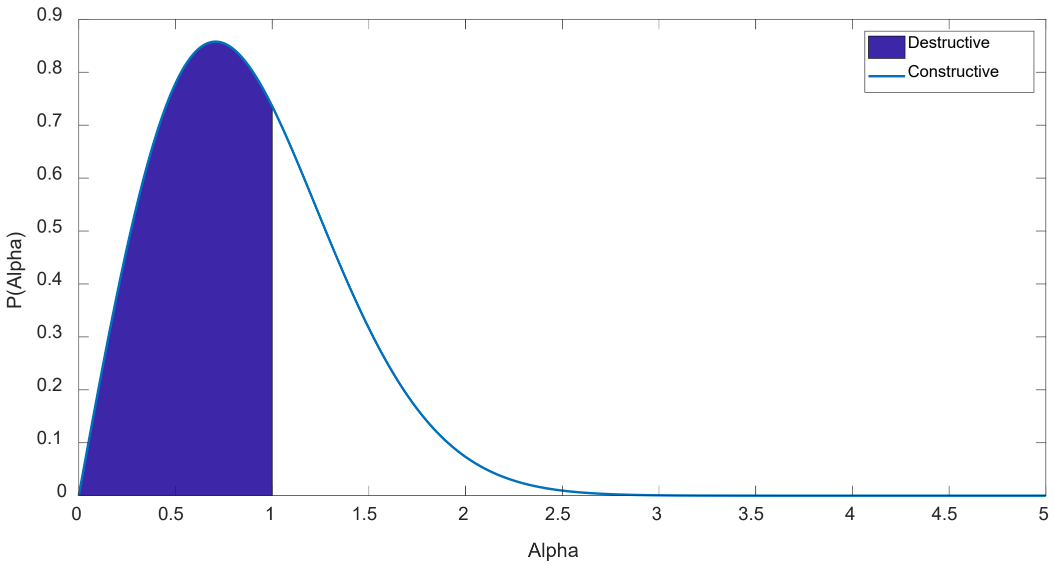

Figure 3.1. PDF of the received signal envelope in a Rayleigh fading channel ($\Omega = 1$)

3.3.3. Noise

The most widely spread form of noise is thermal noise, which is due to thermal agitation of electrons and uniformly distributed across the frequency spectrum and mostly modelled using additive white Gaussian noise model. According to [83], the thermal noise gets generated by random fluctuations of electrons within the conducting media and has a Gaussian distribution with zero mean. From the Nyquist formula, an assumption is made of a resistor to contain a voltage generator across the terminals. The mean square value is

$$v^2 = 4\mathrm{R}k\mathrm{T}\Delta f \tag{3.10}$$

where R is the resistance of the conductor, k is the Boltzmann's constant, T is the absolute temperature and Δf is the signal bandwidth. The average power in a conductor due to thermal noise is equal to

$$P_{thermal} = kTB \tag{3.11}$$

Additive white Gaussian noise (AWGN) is a statistically random radio noise characterized by a Gaussian PDF. AWGN is the most used channel model for a communication system.

AWGN is modelled by adding a white Gaussian noise process to the transmitted signal. The received signal is mathematically expressed as

$$r(t) = s(t) + n(t) \tag{3.12}$$

where $r(t)$ and $s(t)$ are the received and transmitted signals and $n(t)$ is a real zero-mean white Gaussian process with single-sided Power Spectral Density (PSD) of N_0 (W/Hz).

3.4. Massive MIMO

The use of multiple antenna systems is a standard method to overcome fading degradation and combat interference effects. Employing a MIMO system can also help to multiply the capacity of a communication system. Point-to-point MIMO represents the purest form of MIMO, where the transmitter and the receiver are equipped with N_t and N_r antennas, respectively. An alternative approach for employing multiple antennas is the multi-user MIMO (MU-MIMO) system. In an MU-MIMO system, a single BS serves multiple users using the same time-frequency resource. A key component in MU-MIMO systems is the CSI knowledge of the UL channel at the BS. The CSI information is used in the pre-coder design for data transmission in DL and for a linear decoder in detecting the UL transmitted signal at the BS.

Let us assume an MU-MIMO system with K users and an M-antennas BS. In a UL transmission where all users transmit signals over the same time-frequency resources simultaneously, the received vector at the BS is

$$\boldsymbol{r} = \mathbf{G}\boldsymbol{s} + \boldsymbol{n} \tag{3.13}$$

where $\boldsymbol{s} \in \mathbb{C}^{K\times 1}$ and $\boldsymbol{r} \in \mathbb{C}^{M\times 1}$ are the vectors for the transmitted and received signals. $\mathbf{G} \in \mathbb{C}^{M\times K}$ is the transfer channel matrix of the system containing both large and small-scale effects as

$$\mathbf{G} = \mathbf{H}\mathbf{D}^{1/2} \tag{3.14}$$

$\mathbf{H} \in \mathbb{C}^{M \times K}$ denotes the small-scale fading effects modelled by i.i.d. $\mathcal{CN}(0,1)$ elements and $\mathbf{D} \in \mathbb{C}^{K \times K}$ is a diagonal matrix to model the large-scale impairments (i.e., path loss and shadowing). Finally, $\boldsymbol{n} \in \mathbb{C}^{M \times 1}$ represents the AWGN vector modelled by i.i.d. $\mathcal{CN}(0, N_0)$ elements. $\mathbb{C}$ is the field of complex numbers, and it is assumed that $\mathbf{H}, \mathbf{D}$ and $\boldsymbol{n}$ are statistically independent. The detection task in a MIMO system is to estimate $\boldsymbol{s}$ based on the knowledge of $\boldsymbol{r}$. If $\mathbf{G}$ is known at the receiver as a result of CSI, the detection is coherent; otherwise, it is noncoherent.

In a favourable propagation, it is assumed that the small-scale attenuation of different channels are independent and therefore, the following property will be held theoretically when $M \to \infty$ and in practice $M \gg K$ [84]. The proof is based on the law of large numbers and can be found in [84].

$$\frac{\mathbf{G}^{\mathbf{H}}\mathbf{G}}{M} = \mathbf{D}^{1/2} \frac{\mathbf{H}^{\mathbf{H}}\mathbf{H}}{M} \mathbf{D}^{1/2} \approx \mathbf{D} \tag{3.15}$$

Such a system with a larger number of antennas at the BS than the active users is known as the massive MIMO or Large-scale MIMO (LS-MIMO) system. In an LS-MIMO system, M is typically much more significant than K. Moreover, CSI is only required at the BS. A large number of antennas make the beamforming gains constant over frequency. Therefore, the received signal is only affected by the large-scale fading coefficients, which themselves are independent of frequency and antenna index.

In this research, a Zero-Forcing (ZF) detector under a perfect channel estimation at the BS is considered to detect the received UL signals. The ZF filter is equal to

$$\boldsymbol{A} = \mathbf{G}(\mathbf{G}^{\mathbf{H}}\mathbf{G})^{-\mathbf{1}} \tag{3.16}$$

and the received signal, $\boldsymbol{r}$, can then be separated into a vector $\boldsymbol{y} \in \mathbb{C}^{K \times 1}$ as

$$\boldsymbol{y} = \boldsymbol{A}^{\boldsymbol{H}}\boldsymbol{r} = \boldsymbol{s} + (\mathbf{G}^{\mathbf{H}}\mathbf{G})^{-\mathbf{1}}\mathbf{G}^{\mathbf{H}}\boldsymbol{n} = \boldsymbol{s} + \mathbf{D}^{-1/2}(\mathbf{H}^{\mathbf{H}}\mathbf{H})^{-\mathbf{1}}\mathbf{H}^{\mathbf{H}}\boldsymbol{n} \tag{3.17}$$

We denote the signal transmitted by the k^{th} user, which is the k^{th} element of vector $\boldsymbol{s}$, as $[\boldsymbol{s}]_k = s_k$. We further assume the average transmitted power of each user to be P, and so $\mathbb{E}\{|s_k|^2\} = P$ for $k = 1, \dots, K$. The average noise power on the k^{th} stream of the vector $\boldsymbol{y}$ under the favourable propagation constraint can be calculated as

$$\mathbb{E}\{[(\mathbf{G^H G})^{-1}\mathbf{G^H}\boldsymbol{n}]_{kk}\} = \mathbb{E}\{D_k^{-1}(\boldsymbol{h}_k^H\boldsymbol{h}_k)^{-1}|n_k|^2\}$$

$$= D_k^{-1}\mathbb{E}\{(\boldsymbol{h}_k^H\boldsymbol{h}_k)^{-1}\}N_0$$

$$= \frac{\mathbb{E}\{tr[(\mathbf{H^H H})^{-1}]\}}{KD_k}N_0 = \frac{\frac{K}{(M-K)}}{KD_k}N_0 = \frac{1}{(M-K)D_k}N_0 \tag{3.18}$$

where $[\boldsymbol{D}]_{kk} = D_k$. Therefore, the SINR at the BS for the k^{th} user is

$$\mathrm{SINR}_k = (M-K)D_k\frac{P}{N_0} \tag{3.19}$$

The ergodic spectral efficiency of the k^{th} user is then equal to

$$\mathrm{R}_k = \mathbb{E}\left\{\log\left(1 + \frac{P}{[(\mathbf{G^H G})^{-1}]_{kk}N_0}\right)\right\} \geq \log\left(1 + \frac{P}{\mathbb{E}\{[(\mathbf{G^H G})^{-1}]_{kk}\}N_0}\right) \tag{3.20}$$

Where the inequality is based on Jensen's inequality. By substituting (3.19) in (3.20) we get

$$\mathrm{R}_k \geq \log\left(1 + (M-K)D_k\frac{P}{N_0}\right) \tag{3.21}$$

As is seen from (3.17) and (3.21), by increasing the number of antennas, the fast fading effects can be reduced and theoretically vanishes when the number of antennas approaches infinity and the spectral efficiency of the user's increases.

3.5. Summary

In this chapter, the required mathematical background for modelling a D2D communication system, which will be covered in the next chapter, was discussed. This includes different types of impairments that affect a wireless communication system. These impairments are categorized into two groups as large-scale and small-scale effects. Large-scale effects include the variation of the mean received signal strength over large distances, and small-scale effects involve the variation of the mean received signal strength over small distances or short time intervals. The most critical large-scale impairments in a mobile channel are path loss and shadowing. Fast fading, on the other hand, is due to small-scale effects. The use of multiple antenna systems, which is a standard method to overcome fading degradation and combat interference effects, was also discussed. Although different types of filters can be used as the receiving filter, ZF filters can achieve satisfactory performance in cancelling interference in an MU-MIMO system with a large number of antennas.

Chapter 4 : POWER ALLOCATION FOR A QOS-AWARE UNDERLAY D2D COMMUNICATION SYSTEM

4.1. Introduction

The implementation of D2D communication must not affect nearby ongoing communication services. Therefore, resource management is a significant aspect of D2D communication, which aims to reduce interferences. Spectrum and power resources are the primary means that can be employed by interference control mechanisms. By separating the operational spectrum of cellular and D2D communications, the cross-interferences between CUEs and DUEs can be mitigated. Alternatively, when DUEs and CUEs share a spectrum, the interference effects can be limited by careful power allocation.

In this chapter, we study an underlay D2D communication in a cellular system, where the cellular UL spectrum is shared among DUEs and CUEs in a random competitive manner. By strictly controlling the maximum transmission power, DUEs can reuse the UL spectrum without degrading the performance of CUEs communications. The intra-cell cross-interference between DUEs and CUEs in such a system is illustrated in Figure 4.1.

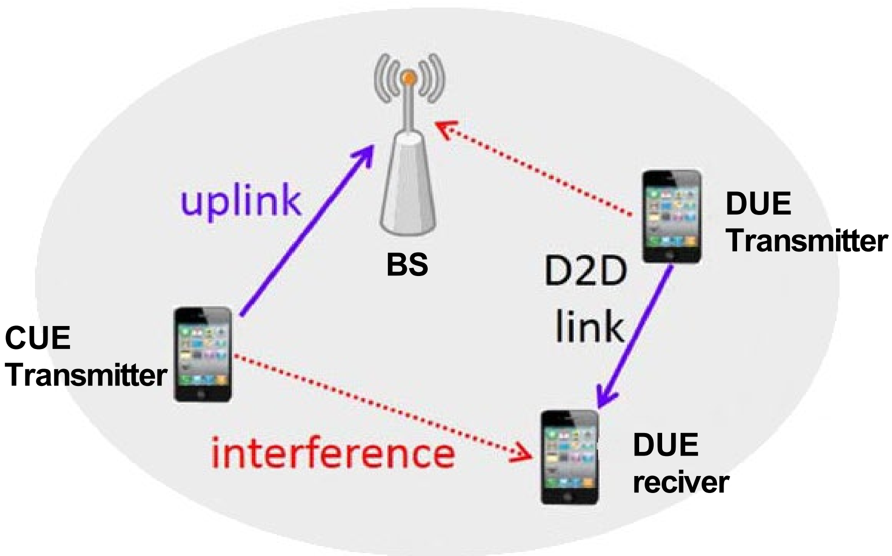

Figure 4.1. Illustration of intra-cell interference for an in-band UL D2D communication system.

In this chapter, we employ the statistical methods for analysing the performance of a D2D communication that underlays the UL of a cellular system. By sharing the UL spectrum for D2D communication, the system can benefit from employing multiple arrays of antennas to control the interference at the BS. We then derive the equations from calculating the minimum transmission power that provides the required spectral efficiency for both CUEs and DUEs, without considering any limitation on the spectrum sharing among devices. As the preference of D2D is for short-distance communications, we only consider D2D links between users that are in each other's LoS.

4.2. System Model

We investigate an underlay D2D communications that share the UL spectrum in a cellular network as in Figure 4.2. This is a standard practice because the uplink resources are less intensively used and CUE interference cancellation becomes more manageable by employing a very large antenna array at the BS. Each mobile device is equipped with a single antenna radio equipment and the BS receiver has M antennas.

DUEs directly communicate with each other in a distributed ad-hoc fashion with no BS assistance, and all mobile users are uniformly distributed over the cell coverage. We only consider intra-cell interferences. Furthermore, the specific modulation and coding schemes were not considered, and only the signals' power levels were considered.

The set of mobile devices involved in cellular communication in a cell are denoted by $\mathcal{C} = 1,2,\ldots,N$ and the pair of devices involved in D2D communication as $\mathcal{D} = 1,2,\ldots,O$. We assume a fully-loaded network, where the active CUEs occupy all N orthogonal channels in the cell, and there is no spare spectrum. As the BS contains M antenna, the baseband received signal at the BS, $\boldsymbol{r}^{(c)} \in \mathbb{C}^{M\times 1}$, is equal to

$$\boldsymbol{r}^{(c)} = \sum_{k\in\mathcal{C}} \sqrt{A^{(c)}\beta_k^{(c)}}(d_k)^{-\frac{\alpha_c}{2}}\boldsymbol{h}_k u_k^{(c)} + \sum_{i\in\mathcal{D}} \sqrt{A^{(c)}\beta_i^{(c)}}(d_i)^{-\frac{\alpha_c}{2}}\boldsymbol{h}_i u_i^{(d)} + \boldsymbol{n} \tag{4.1}$$

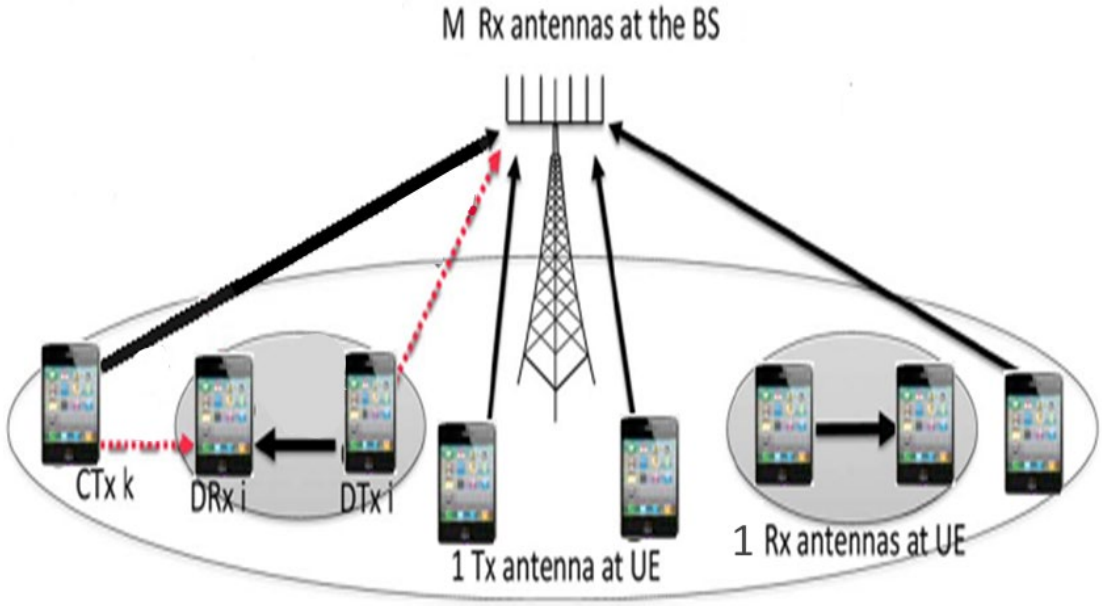

Figure 4.2. A D2D underlaid massive MIMO system consisting of both CUEs and DUEs [7].

The large-scale attenuation effect consists of shadowing and path loss. Following the models provided in chapter 3, the path loss would affect the transmitted signal's magnitude by a factor of

$$\sqrt{A^{(c)}}(d)^{-\frac{\alpha_c}{2}} \tag{4.2}$$

where d denotes the distance between a mobile device (either CUE or DUE) and BS, $\alpha_c > 2$ is the path loss exponent, and $A^{(c)}$ is the path loss constant that depends on the antenna height and carrier frequency. Also, as a result of the shadowing, the signal magnitude is affected by a factor of

$$\sqrt{\beta^{(c)}} \tag{4.3}$$

where $\beta^{(c)}$ is modelled as i.i.d. log-normal shadow fading random variables with $10 \log \beta^{(c)} \sim \mathcal{N}(0, \sigma_{sc}^2)$.

The effects of small-scale fading are denoted by $\boldsymbol{h} \in \mathbb{C}^{M\times 1}$, and its elements are taken as i.i.d. complex Gaussian random variable distributed by $\mathcal{CN}(0,1)$. $\boldsymbol{n}$ denotes additive white Gaussian noise (AWGN) vector, which its elements are i.i.d. random variables distributed by $\mathcal{CN}(0,\ N_0)$. $u^{(c)}$ and $u^{(d)}$ are the transmitted signals by the CUEs and DUEs, respectively. They are modelled as i.i.d. random variables with $\mathbb{E}\left\{\left|u^{(c)}\right|^2\right\} = P_c$ and $\mathbb{E}\left\{\left|u^{(d)}\right|^2\right\} = P_d$.

The received signal at the i^{th} DUE's receiver is

$$r_i^{(d)} = \sqrt{A^{(d)}}(d_{ii})^{-\frac{\alpha_d}{2}} g_{ii} u_i^{(d)} + \sum_{k\in\mathcal{C}} \sqrt{A^{(d)}\beta_k^{(d)}}(d_{ik})^{-\frac{\alpha_d}{2}} g_{ik} u_k^{(c)}$$

$$+ \sum_{\substack{j\in\mathcal{D}\\ j\neq i}} \sqrt{A^{(d)}\beta_j^{(d)}}\left(d_{ij}\right)^{-\frac{\alpha_d}{2}} g_{ij} u_j^{(d)} + n \qquad (4.4)$$

where d_{ik} is the distance between mobile device i and mobile device k, $\alpha_d > 2$ denotes the path loss exponent between two devices, and $\beta^{(d)}$ are i.i.d. log-normal shadow fading random variables distributed as $10\log\beta^{(d)} \sim \mathcal{N}(0, \sigma_{sd}^2)$.

The effects of small-scale fading are denoted by g, which are i.i.d. $\mathcal{CN}(0,1)$ variables. n is due to AWGN and has complex Gaussian distribution of $\mathcal{CN}(0, N_0)$. We assume$u^{(c)}$ and $u^{(d)}$ are i.i.d. random variables where $\mathbb{E}\left\{\left|u^{(c)}\right|^2\right\} = P_c$ and $\mathbb{E}\left\{\left|u^{(d)}\right|^2\right\} = P_d$.

Let us assume $\boldsymbol{w}_m^{(c)}$ is the filter used by the BS for receiving the signal from the *m*th CUE transmitter. Therefore, the averaged received SINR at the BS from the *m*th CUE link can be expressed as

$$\gamma_m^{(c)} = \frac{S_m^{(c)}}{I_m^{(c\to c)} + I_m^{(d\to c)} + \left\|\boldsymbol{w}_m^{(c)*}\right\|^2 N_0} \qquad (4.5)$$

where

$$S_m^{(c)} = P_c A^{(c)} \beta_m^{(c)} (d_m)^{-\alpha_c} \left\| \boldsymbol{w}_m^{(c)^*} \boldsymbol{h}_m \right\|^2 \tag{4.6}$$

is desired signal power

$$I_m^{(c\to c)} = \sum_{\substack{k\in\mathcal{C} \\ k\neq m}} P_c A^{(c)} \beta_k^{(c)} (d_k)^{-\alpha_c} \left\| \boldsymbol{w}_m^{(c)^*} \boldsymbol{h}_k \right\|^2 \tag{4.7}$$

is the interference as a result of CUEs other than *m*th CUE and

$$I_m^{(d\to c)} = \sum_{i\in\mathcal{D}} P_d A^{(c)} \beta_i^{(c)} (d_i)^{-\alpha_c} \left\| \boldsymbol{w}_m^{(c)^*} \boldsymbol{h}_i \right\|^2 \tag{4.8}$$

is the interference caused by DUEs. Similarly, the received SINR at the mth DUE receiver can be expressed as

$$\gamma_m^{(d)} = \frac{S_m^{(d)}}{I_m^{(c\to d)} + I_m^{(d\to d)} + \left\| w_m^{(d)^*} \right\|^2 N_0} \tag{4.9}$$

where

$$S_m^{(d)} = P_d A^{(d)} \beta_m^{(d)} (d_{mm})^{-\alpha_d} \left\| w_{mk}^{(d)^*} g_{mm} \right\|^2 \tag{4.10}$$

is the desired signal power,

$$I_m^{(c\to d)} = \sum_{k\in\mathcal{C}} P_c A^{(d)} \beta_k^{(d)} (d_{mk})^{-\alpha_d} \left\| w_{mk}^{(d)^*} g_{mk} \right\|^2 \tag{4.11}$$

is the interference as a result of CUEs and

$$I_m^{(d\to d)} = \sum_{\substack{i\in\mathcal{D} \\ i\neq m}} P_d A^{(d)} \beta_i^{(d)} (d_{mi})^{-\alpha_d} \left\| w_{mk}^{(d)^*} g_{mi} \right\|^2 \tag{4.12}$$

is the interference caused by other D2D links.

The ergodic spectrum efficiency of the cellular link for the *m*th CUE is

$$R_m^{(c)} = \mathbb{E}\left\{\log\left(1+\gamma_m^{(c)}\right)\right\} \tag{4.13}$$

Moreover, the ergodic spectrum efficiency of the *m*th DUEs pair is

$$R_m^{(d)} = \mathbb{E}\left\{\log\left(1+\gamma_m^{(d)}\right)\right\} \tag{4.14}$$

For achieving the ergodic spectrum efficiencies of the links, no prior knowledge about the location of the users or the CSI is required.

4.3. Power Allocation

In many applications, achieving a minimum QoS requirement for DUEs and CUEs are essential. As it is seen from (4.13) and (4.14), the minimum QoS is directly proportional to $\gamma_m^{(c)}$ and $\gamma_m^{(d)}$ for the *m*th CUE and DUE, respectively. However, it can be deduced from (4.9) that if DUEs control their power entirely, a CUE can achieve the required QoS. This is mutually applicable to achieving a required performance by DUE as a result of strict control over CUE transmission power.

Employing a BS with M antennas offers a significant opportunity for achieving the desired QoS in CUE links. It is shown in [54] that if a BS contains a large array of antennas (M →∞) and has the capability of obtaining the perfect CSI through the transmission of training sequences, then by designing $\boldsymbol{w}_m^{(c)}$ as a ZF filter, $\gamma_m^{(c)}$ can increase unboundedly and therefore, any desired capacity is achievable.

However, having a perfect CSI in an environment that contains high mobility among users is not practical. To overcome this limitation, a training sequence needs to be transmitted every few hundred milliseconds for CSI estimation. The CUE spectral efficiency of a system that has a BS with a large array of antennas and an estimated CSI based on training sequences of length T_c $(T_c > N)$ for N cellular users is achieved according to [54] as

$$R_m^{(c)} = \mathbb{E}\left\{\log\left(1 + \frac{T_c P_c^2 \left(A^{(c)} \beta_m^{(c)}\right)^2 (d_m)^{-2\alpha_c}}{\sum_{i\in\mathcal{D}} P_d^2 \left(A^{(c)} \beta_i^{(c)}\right)^2 (d_i)^{-2\alpha_c}}\right)\right\} \geq \log\left(1 + \frac{T_c P_c^2}{\mathcal{D} P_d^2}\right) \tag{4.15}$$

Therefore, the minimum capacity requirement of CUE links, $R_0^{(\mathrm{cue})}$, can be used to calculate the required transmission power, P_c and P_d, such that $R_m^{(c)} \geq R_0^{(\mathrm{cue})}$ for all m.

The preference of D2D is for short-distance communications. Therefore, we consider the D2D links between DUEs that are in each other's LoS. The D2D spectral efficiency given in (4.14) for this system can be calculated based on $S_m^{(d)} = P_d A^{(d)} (d_{mm})^{-\alpha_d}$. The minimum capacity requirement of the D2D links is then equal to $R_0^{(\mathrm{due})}$ and $R_m^{(d)} \geq R_0^{(\mathrm{due})}$.

By considering that $\gamma_m^{(d)}$ is a convex function of $\left\{\beta_i^{(d)}\right\}$, $\{g_{mi}\}$ and $\{d_{ii}\}$ we have

$$\begin{aligned} R_m^{(d)} = \mathbb{E}\left\{\log\left(1 + \gamma_m^{(d)}\right)\right\} &\geq \log\left(1 + \frac{P_d}{\mathbb{E}\left\{\beta_i^{(d)}\right\}(NP_c + (0-1)P_d) + \frac{N_0}{A^{(d)}}(\mathbb{E}\{d_{mi}\})^{\alpha_d}}\right) \\ &\geq \log\left(1 + \frac{P_d}{(NP_c + (0-1)P_d) + \frac{N_0}{A^{(d)}}(\mathbb{E}\{d_{mi}\})^{\alpha_d}}\right) \end{aligned} \tag{4.16}$$

The convexity of $\log\left(1+\frac{1}{x}\right)$ can easily be proved as $\frac{d^2}{dx^2}\log\left(1+\frac{1}{x}\right)=\frac{1}{\ln 2}\frac{2x+1}{(x^2+x)^2}>0$ and the convexity of $\frac{1}{1+x}$ is proved by $\frac{d^2}{dx^2}\frac{1}{1+x}=\frac{2}{(1+x)^3}>0$ knowing that $x>0$.

We model the spatial positions of the user equipments as a Poisson point process (PPP). Therefore, for a user equipment m located at (x_0, y_0) and user equipment i located at (x_1, y_1) we have

$$d_{mi}=\sqrt{(x_0-x_1)^2+(y_0-y_1)^2}=\sqrt{(r_0-r_1\cos\theta)^2+(r_1\sin\theta)^2}$$

$$=\sqrt{r_0^2+r_1^2-2r_1r_0\cos\theta} \tag{4.17}$$

Without loss of generality, we can assume user equipment m angular position is at zero. For a circular cell with the coverage radius of R, r_0 and r_1 are uniformly distributed in the range of $[0, R]$. Moreover, θ is uniformly distributed in the range of $[0, \pi]$. The expected value for the distance between two randomly located user equipments are achieved from [85] as

$$\mathbb{E}\{d_{mi}\}=\frac{1}{\pi R^2}\iiint_{r_0,r_1,\theta}\sqrt{r_0^2+r_1^2-2r_1r_0\cos\theta}\,dr_0dr_1d\theta=\frac{128}{45\pi}R \tag{4.18}$$

By simultaneously solving (4.15) and (4.16), the minimum required P_d and P_c will then be achieved as

$$P_d=\frac{\frac{N_0}{A^{(d)}}\left(\frac{128}{45\pi}R\right)^{\alpha_d}}{\left(2^{R_0^{(\mathrm{due})}}-1\right)^{-1}-(\mathrm{O}-1)-N\sqrt{(\mathrm{O}-1)\left(2^{R_0^{(\mathrm{cue})}}-1\right)}} \tag{4.19}$$

$$P_c=\sqrt{(\mathrm{O}-1)\left(2^{R_0^{(\mathrm{cue})}}-1\right)}\,P_d \tag{4.20}$$

that gives us the required transmission power for DUEs and CUEs to achieve the desired transmission rate in an average statistical sense.

4.4. Summary

In this chapter, we have investigated an underlay D2D communications that share the UL spectrum of a cellular network, which benefits from a large array of the antenna at the BS. The concept of massive MIMO has been considered to minimise the interference in the user-to-cellular link. We have employed a statistical method to analyse the performance of the system without considering any prior knowledge about the location of the users, the CSI, or any limitation on the spectrum sharing among devices. We achieved the required power in a QoS-aware system by calculating the minimum transmission power that will provide the required spectral efficiency for both CUEs and DUEs.

Chapter 5 : POWER ALLOCATION FOR A D2D-ENABLED VEHICULAR COMMUNICATION SYSTEM

5.1. Introduction

Cellular-based V2X was proposed by the 3GPP in Release 14 of LTE (LTE-V2V) and had the potential to offer the required performances needed by ADAS applications. Moreover, it can benefit from the already available and almost ubiquitous coverage of cellular LTE systems. D2D communication enables the nearby mobile devices to communicate with one another without the data traversing the core network or a cellular BS, and therefore, can be considered as a promising solution for reliable and efficient V2V links. Furthermore, the V2I links can be supported by Device-to-eNodeB links in a cellular-based V2X.

In this chapter, a cellular-based vehicular communication system is considered that employs underlay D2D for establishing V2V links between vehicles. The complete uplink spectrum of a cellular system is shared with the underlay D2D communication system for this purpose. All vehicles can be involved in V2V or V2I communications without any limitation, but each V2V link only shares the spectrum with one V2I link at a time. We have employed the achieved results from the previous chapter to analyse the performance of the system without considering any prior knowledge about the location of the vehicles or the CSI.

This chapter aims to find boundaries on the allocated transmission powers to achieve sufficient spectral efficiencies for V2I and V2V links. For this purpose, we use the concept of massive MIMO to cancel the interference in the V2I links. We then derive the equations for calculating the minimum required transmission power to establish each link. As the preference of ADAS applications is to monitor a vehicle's surrounding environment for detecting hazardous conditions, we consider the V2V links between vehicles that are in each other's LoS.

5.2. System Model

Consider a cellular-based VANET shown in Figure 5.1. The V2V connections are supported by underlay D2D communication, which reuses the cellular uplink spectrum. This is a standard practice because the uplink resources are less intensively used and V2I interference cancellation becomes more manageable by employing a very large antenna array at the BS, as was mention in the previous chapter. Each vehicle is equipped with a single antenna radio equipment, and the BS receiver has M antennas. Therefore, a vehicle can either be involved in V2I or V2V communication at a time. We only consider intra-cell interferences in this chapter.

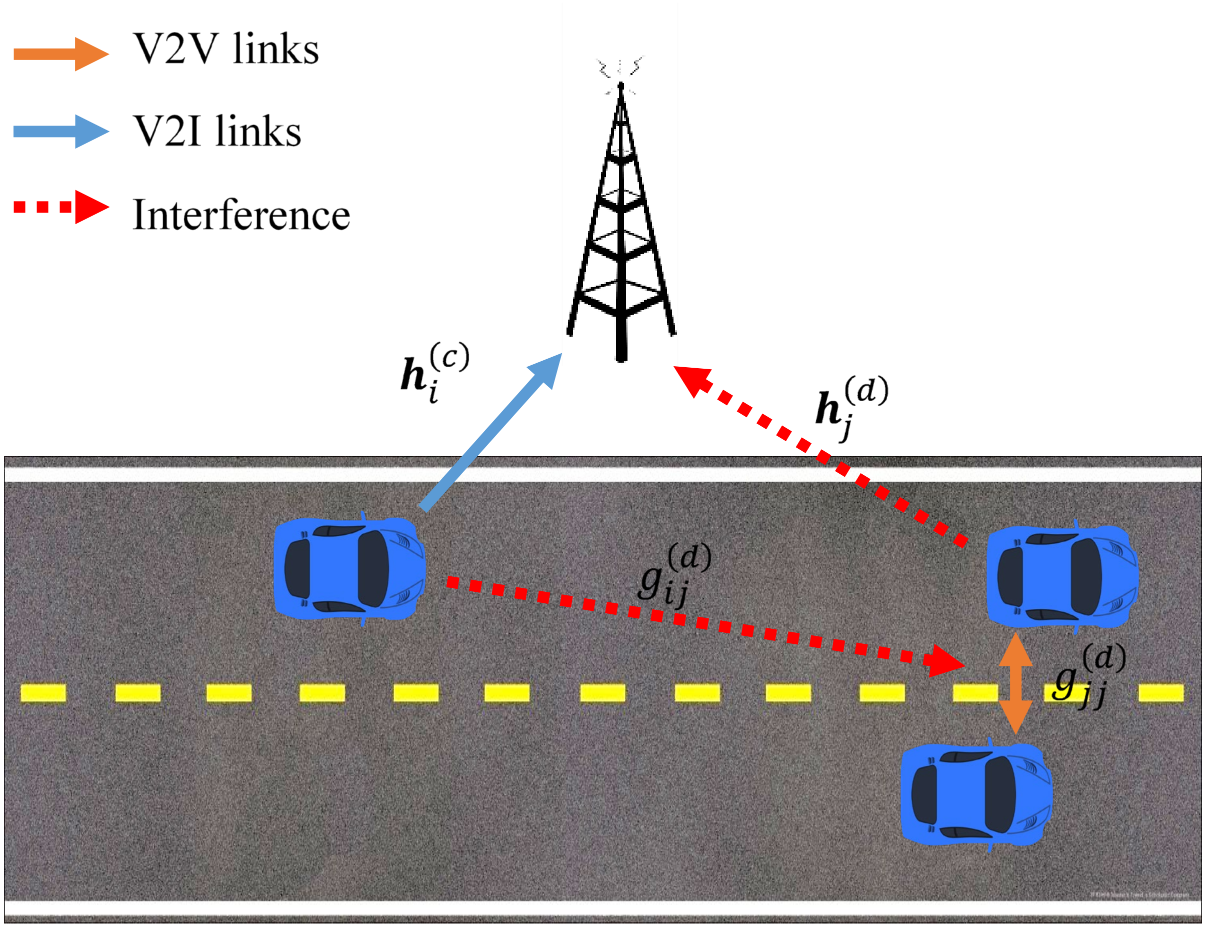

Figure 5.1. A vehicular communication network based on that employed underlay D2D sharing the cellular uplink spectrum.

We denote the set of vehicles in a cell that is involved in V2I communication by $\mathcal{J}$=1,2,…, I and those that are involved in V2V communication by $\mathcal{V}$=1,2,…, V. Figure 5.1 illustrates a V2V link between the pair $j\epsilon\mathcal{V}$ and a V2I link between the vehicle $i\epsilon\mathcal{J}$ and the BS.

The M×1 dimensional baseband received signal at the BS, which is as a result of V2I communication is

$$\boldsymbol{r}^{(c)} = \sum_{i\in\mathcal{J}} \sqrt{P_c A^{(c)} \beta_i^{(c)}} (d_i)^{-\frac{\alpha_c}{2}} \boldsymbol{h}_i^{(c)} u_i^{(c)} + \sum_{j\in\mathcal{V}} \sqrt{P_d A^{(c)} \beta_j^{(c)}} (d_j)^{-\frac{\alpha_c}{2}} \boldsymbol{h}_j^{(d)} u_j^{(d)} + \boldsymbol{n}^{(c)} \quad (5.1)$$

where P_c and P_d are the V2I and V2V transmission power, respectively. The large-scale attenuation effect consists of shadowing and path loss.

Similar to the previous chapter, the Path loss is equal to $\left\{\sqrt{A^{(c)}}(d_i)^{-\frac{\alpha_c}{2}}\right\}$, where d_i denotes the distance between vehicle i and BS. $\alpha_c > 2$ is the path loss exponent, and $A^{(c)}$ is the path loss constant depending on the antenna height and carrier frequency. The shadowing effect is modelled by $\left\{\sqrt{\beta_i^{(c)}}\right\}$, where $\left\{\beta_i^{(c)}\right\}$ are i.i.d. log-normal shadow fading random variables with $10\log\beta_i^{(c)} \sim\mathcal{N}(0,\sigma_{sc}^2)$.

The effects of small-scale fading are denoted by $\boldsymbol{h}_i^{(c)}$and $\boldsymbol{h}_j^{(d)}$, where the elements of $\boldsymbol{h}_i^{(c)}$and $\boldsymbol{h}_j^{(d)}$ are taken as i.i.d. complex Gaussian random variable distributed by $\mathcal{CN}(0,1)$. $\boldsymbol{n}^{(c)}$ denotes additive white Gaussian noise (AWGN) vector, which its elements are i.i.d. random variables distributed by $\mathcal{CN}(0, N_0)$.

The received signal at the receiving vehicle of the k^{th} pair involved in V2V communication is

$$r_k^{(d)} = \sum_{i\in\mathcal{I}} \sqrt{P_c A^{(d)} \beta_i^{(d)}} (d_{ik})^{-\frac{\alpha_d}{2}} g_{ik}^{(d)} u_i^{(c)} + \sum_{j\in\mathcal{V}} \sqrt{P_d A^{(d)} \beta_j^{(d)}} (d_{jk})^{-\frac{\alpha_d}{2}} g_{jk}^{(d)} u_j^{(d)} + n^{(d)} \quad (5.2)$$

where d_{ik} is the distance between the transmitting vehicle i and the receiver vehicle of the *k*th pair. $\alpha_d > 2$ denotes the path loss exponent, and $\left\{\beta_i^{(d)}\right\}$ are i.i.d. log-normal shadow fading random variables distributed as $10\log\beta_i^{(d)} \sim \mathcal{N}(0, \sigma_{sd}^2)$.

The effects of small-scale fading are denoted by $g_{ik}^{(d)}$, which are i.i.d. $\mathcal{CN}(0,1)$ variables. $n^{(d)}$ is AWGN with complex Gaussian distribution of $\mathcal{CN}(0, N_0)$. For this paper, we assume $\left\{u_i^{(c)}\right\}$, $\left\{u_j^{(d)}\right\}$ are i.i.d. random variables distributed by $\mathcal{CN}(0,1)$.

Let us assume $\boldsymbol{w}_m^{(c)}$ is the filter used by the BS for receiving the V2I signal from the *m*th vehicle transmitter. Therefore, the received SINRs at the BS from the *m*th vehicle V2I link can be expressed as

$$\gamma_m^{(c)} = \frac{S_m^{(c)}}{I_m^{(c\to c)} + I_m^{(d\to c)} + \left\|\boldsymbol{w}_m^{(c)^*}\right\|^2 N_0} \quad (5.3)$$

$$S_m^{(c)} = P_c A^{(c)} \beta_m^{(c)} (d_m)^{-\alpha_c} \left\|\boldsymbol{w}_m^{(c)^*} \boldsymbol{h}_m^{(c)}\right\|^2 \quad (5.3a)$$

$$I_m^{(c\to c)} = \sum_{\substack{i\in\mathcal{I}\\ i\neq m}} P_c A^{(c)} \beta_i^{(c)} (d_i)^{-\alpha_c} \left\|\boldsymbol{w}_m^{(c)^*} \boldsymbol{h}_i^{(c)}\right\|^2 \quad (5.3b)$$

$$I_m^{(d\to c)} = \sum_{j\in\mathcal{V}} P_d A^{(c)} \beta_j^{(c)} (d_j)^{-\alpha_c} \left\|\boldsymbol{w}_m^{(c)^*} \boldsymbol{h}_j^{(d)}\right\|^2 \quad (5.3c)$$

Where (5.3a) gives the desired signal power, (5.3b) is the interference as a result of V2I from vehicles other than mth vehicle, and (5.3c) is the interference caused by V2V links. Similarly, the received SINRs at the receiving vehicle of the mth pair involved in V2V communication can be expressed as

$$\gamma_m^{(d)} = \frac{S_{mm}^{(d)}}{I_m^{(c\to d)} + I_m^{(d\to d)} + N_0} \tag{5.4}$$

$$S_{mm}^{(d)} = P_d A^{(d)} \beta_m^{(d)} (d_{mm})^{-\alpha_d} \left\| g_{mm}^{(d)} \right\|^2 \tag{5.4a}$$

$$I_m^{(c\to d)} = \sum_{i\in\mathcal{I}} P_c A^{(d)} \beta_i^{(d)} (d_{im})^{-\alpha_d} \left\| g_{im}^{(d)} \right\|^2 \tag{5.4b}$$

$$I_m^{(d\to d)} = \sum_{\substack{j\in\mathcal{V} \\ j\neq m}} P_d A^{(d)} \beta_j^{(d)} \left(d_{jm}\right)^{-\alpha_d} \left\| g_{jm}^{(d)} \right\|^2 \tag{5.4c}$$

where (5.4a) is the desired signal power, (5.4b) is the interference as a result of V2I links, and (5.4c) is the interference caused by other V2V links. The ergodic spectrum efficiency of the V2I link for the mth vehicle is

$$R_m^{(c)} = \mathbb{E}\left\{\log\left(1 + \gamma_m^{(c)}\right)\right\} \tag{5.5}$$

also, the V2V link between the kth and mth vehicles is

$$R_m^{(d)} = \mathbb{E}\left\{\log\left(1 + \gamma_m^{(d)}\right)\right\} \tag{5.6}$$

5.3. Power Allocation

ADAS can benefit from the Mobile edge computing (MEC) concept for accessing their required computational and storage capacities remotely. In such a system, vehicles should be able to upload their sensors' data to MEC servers for further processing. Vehicular communication is the enabler for designing such driver assistance systems, which would operate based on collaborative and remote processing solutions. The requirements for a VANET to support ADAS are V2I links that have large throughputs and V2V links with high reliability.

Employing a BS with multiple antennas will offer a significant opportunity to achieve the desired QoS in V2I links. It is shown in the previous chapter if a BS contains a large array of antennas (M →∞) and has the capability of obtaining the perfect CSI through the transmission of training sequences, then by designing $\boldsymbol{w}_m^{(c)}$ as a ZF filter, $\gamma_m^{(c)}$ can increase unboundedly and therefore, any desired capacity can be achieved. However, having a perfect CSI in a vehicular environment that contains high mobility is not practical.

To overcome this limitation, a training sequence needs to be transmitted every few hundred milliseconds for CSI estimation. By extending the results that are achieved in the previous chapter, the V2I spectral efficiency of a system that has a BS with a large array of antennas and ZF filters and also uses a training sequence of length T_c for CSI estimation is equal to

$$R_m^{(c)} = \mathbb{E}\left\{\log\left(1+\frac{T_c P_c^2\left(A^{(c)}\beta_m^{(c)}\right)^2 (d_m)^{-2\alpha_c}}{\sum_{j\in\mathcal{V}} P_d^2\left(A^{(c)}\beta_j^{(c)}\right)^2 \left(d_j\right)^{-2\alpha_c}}\right)\right\} \geq \log\left(1+\frac{T_c P_c^2}{\mathcal{V}P_d^2}\right) \tag{5.7}$$

If the minimum capacity requirement of V2I links is considered as $R_0^{(\mathrm{V2I})}$, then (5.7) can be used to calculate the required transmission power (P_c and P_d) such that $R_m^{(c)} \geq R_0^{(\mathrm{V2I})}$ for all m.

On the other hand, the preference for ADAS applications is to monitor a vehicle's surrounding environment for detecting hazardous conditions. Therefore, we consider the V2V links between vehicles that are in each other's LoS. The V2V spectral efficiency given in (5.6) for this system can then be calculated based on $S_{mm}^{(d)} = P_d A^{(d)} (d_{mm})^{-\alpha_d}$ therefore if the minimum capacity requirement of the V2V links is considered as $R_0^{(\mathrm{V2V})}$ then $R_m^{(d)} \geq R_0^{(\mathrm{V2V})}$ for all m.

As $\gamma_m^{(d)}$ is a convex function of $I_m^{(c\to d)}$ and $I_m^{(d\to d)}$ therefore based on Jensen's inequality we have

$$R_m^{(d)} = \mathbb{E}\left\{\log\left(1+\gamma_m^{(d)}\right)\right\} \geq \log\left(1+\frac{S_{mm}^{(d)}}{\mathbb{E}\left\{I_m^{(c\to d)} + I_m^{(d\to d)}\right\} + N_0}\right) \tag{5.8}$$

For all $i \neq m$, $\left\{\beta_i^{(d)}\right\}$, $\left\{g_{im}^{(d)}\right\}$ and $\{d_{im}\}$ are independent and $\mathbb{E}\left\{\beta_i^{(d)}\right\}$=$\mathbb{E}\left\{\left\|g_{im}^{(d)}\right\|^2\right\}$=1. Therefore,

$$R_m^{(d)} \geq \log\left(1+\frac{P_d (d_{mm})^{-\alpha_d}}{(\mathcal{J}P_c + (\mathcal{V}-1)P_d)\mathbb{E}\{(d_{im})^{-\alpha_d}\} + \frac{N_0}{A^{(d)}}}\right) \tag{5.9}$$

Let L be the length of the road under the BS coverage, and the spatial positions of the vehicles are modelled as a PPP with intensity λ. Therefore, the probability mass function for the number of vehicles on the road is

$$p\left(\mathcal{J}+\frac{\mathcal{V}}{2}=n\right) = e^{-\lambda L}\frac{(\lambda L)^n}{n!} \tag{5.10}$$

Moreover, the probability distribution function for the distance between vehicles is

$$f(d) = \left(\frac{1}{\lambda L}\right) e^{-d/\lambda L} \tag{5.11}$$

which makes

$$\mathbb{E}\{(d_{im})^{-\alpha_d}\} = \int_{d_{mm}}^{L} x^{-\alpha_d} \left(\frac{1}{\lambda L}\right) e^{-\frac{x}{\lambda L}}\, dx \tag{5.12}$$

By simultaneously solving (5.7) and (5.9), the minimum required P_d and P_c and the constraint on the distance between vehicles for allowing V2V can be achieved as

$$P_d = \frac{\frac{N_0}{A^{(d)}}}{\left(2^{R_0^{(V2V)}} - 1\right)^{-1} (d_{mm})^{-\alpha_d} - \left(\mathcal{J}\sqrt{\mathcal{V}\left(2^{R_0^{(V2I)}} - 1\right)} + \mathcal{V} - 1\right) \int_{d_{mm}}^{L} x^{-\alpha_d} \left(\frac{1}{\lambda L}\right) e^{-\frac{x}{\lambda L}}\, dx} \tag{5.13}$$

$$P_c = \sqrt{\mathcal{V}\left(2^{R_0^{(V2I)}} - 1\right)}\, P_d \tag{5.14}$$

5.4. Summary

Remote computing solutions can enable a highly efficient and cost-effective ADAS for future generation vehicles, and vehicular communication is the enabler for such a method through allowing vehicles to communicate with remote servers by uploading their sensor data for further processing. Large capacity links for V2I connections and high-reliability links for V2V connections are the QoS requirements for a VANET to support ADAS. The V2V and V2I links can respectively be supported by D2D and Device-to-eNodeB links in a cellular-based V2X. However, resource management is very crucial, as the cellular communication and the in-band D2D links cause cross interferences on one another, as they both transmit over the same frequency spectrum. In this paper, we used the concept of massive MIMO to cancel the interference in the V2I links. The underlay D2D communication on the uplink spectrum is employed for V2V links. We derived the equations from calculating the minimum transmission power to achieve the required spectral efficiency for both V2I and V2V links.

Chapter 6 : RESULTS AND DISCUSSION

6.1. Introduction

In this chapter, we provide a numerical analysis to demonstrate the effect of transmission power on the V2I and V2V spectral efficiencies. The specific parameters used are summarized in Table 6.1. The parameters are according to 3GPP TR 36.885 [86].

Table 6.1. Simulation parameters

BS Coverage L	500 m
The density of vehicles λ	1/50 m^{-1}
V2I pathloss reference $A^{(c)}$	15.3 dB
V2V pathloss reference $A^{(d)}$	38.5 dB
V2I pathloss pathloss exponent α_c	3.76
V2V pathloss pathloss exponent α_d	4.37
V2I Lognormal Shadowing σ_{sc}	7 dB
V2V Lognormal Shadowing σ_{sd}	3 dB
Noise PSD	-114 dBm/Hz
Channel bandwidth	10 MHz

6.2. Simulation Results and Discussions

Vehicles are distributed according to homogeneous PPP with intensity λ. The shadowing is lognormal with a deviation σ_{sc} (dB) and σ_{sd} (dB) for V2I and V2V accordingly. The difference is a result of antenna height in the BS and vehicle receiver. The BS has a large array of antennas, and a CSI is estimated based on training sequences. Based on the given values

$$\mathbb{E}\{(d_{im})^{-\alpha_d}\} = \int_{d_{mm}}^{500} 0.1x^{-4.37}e^{-0.1x}\,dx \tag{6.1}$$

From (5.7) we can write

$$P_c = \sqrt{\mathcal{V}\left(2^{R_0^{(\mathrm{V2I})}} - 1\right)}\,P_d \tag{6.2}$$

This shows for maintaining QoS on V2I links, as the number of V2V links increases, the transmission power should also be increased. Also (6.2) provides a guideline for the power ratio between different transmission links. Figure 6.1 shows the power ratio of V2I to V2V links for different spectral efficiencies. As it is seen, more transmission power is required at a higher $R_0^{(\mathrm{V2I})}$ for maintaining the QoS affected by increasing the number of V2V links.

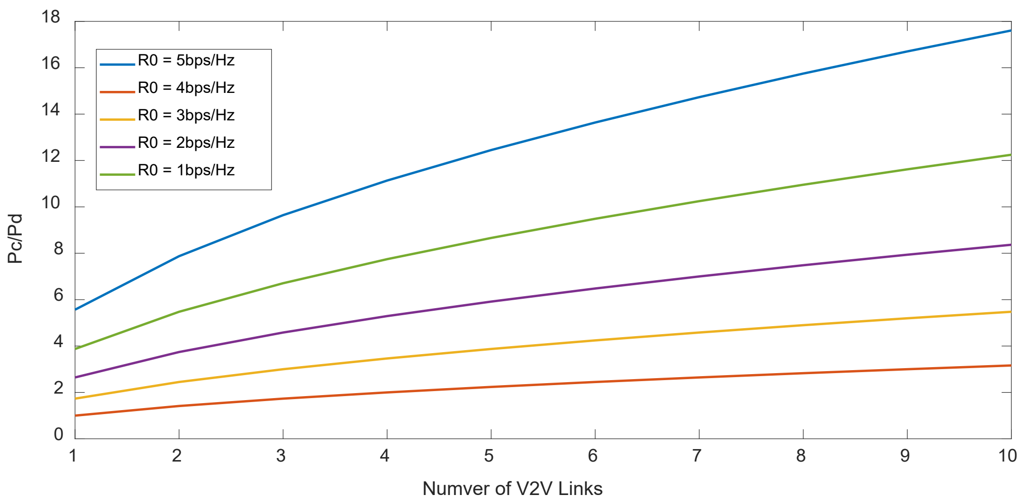

Figure 6.1. The transmission power ratio of V2I to V2V links for different spectral efficiencies values of the V2I link.

Figure 6.2 shows the spectral efficiencies of V2V links for the power ratio of 10. In this figure, $R_m^{(d)}$ has been calculated using (5.12) and (6.1) for the $P_c = 23\ dBm$ and $P_d = 13\ dBm$. As it can be seen by increasing the number of V2V communications, the QoS in the V2V links becomes degraded. This is as a result of interferences, which are added to the system from each extra V2V communication between vehicles.

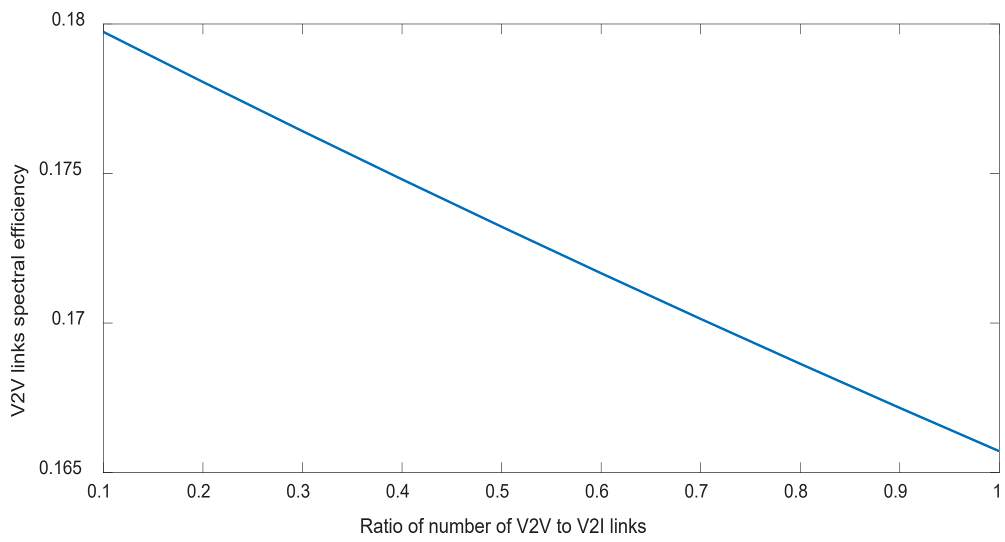

Figure 6.2. The relation between V2V links spectral efficiencies and the ratio of V2V to V2I links.

Chapter 7 : CONCLUSION

In this dissertation, a method to calculate the minimum transmission power for providing the required spectral efficiency and mitigating the interference between the Cellular User Equipments and Device-to-Device User Equipments of a cellular network was proposed. We only consider D2D links between devices that are in each other's line-of-sight. Other than that, no other limitations have been considered. Furthermore, we expand this idea to a cellular-based vehicular communication system, which employs the concept of D2D communication for establishing V2V transmission links.

In chapter 1, the motivation for this research and an overview of the dissertation was given. Vehicular communications and remote processing solutions can be considered as enablers for designing cost-effective ADAS in future vehicles. D2D communication is a suitable candidate for being used in a cellular-based vehicular communication system to support V2V links. D2D communication links, generally, should have minimal or no interference effects on the nearby ongoing cellular communication, and therefore, resource management is a requirement for achieving this goal. Nearby mobile devices can communicate directly without their information traversing through the cellular base station or the evolved NodeB, and as a result, D2D links can provide low-latency, high data-rate communications while consuming relatively less amount of power.

The existing literature on D2D communications and the cellular-based vehicular communication systems was reviewed in chapter 2. D2D communications are considered as one of the solutions for improving spectrum utilization in the next generation of cellular networks. D2D communications can increase the overall capacity of a cellular network. They can also enhance the coverage of a cellular network, especially on the edges of a cell, by allowing BS to access the out-of-coverage DUEs through CUEs that receive adequate levels of signal power. As the distances between DUE's are shorter, D2D communication links can use less power to transmit higher data-rates with shorter delays. However, by adding D2D users to a cellular network, radio resource management becomes a critical part of achieving the required level of QoS. Many applications can be considered for D2D communications, such as high-volume content sharing of videos, pictures, and gaming. D2D communications are also well suited for establishing V2V links between nearby vehicles, and it has been shown in previous studies that D2D-assisted vehicular communication can surpass traditional V2V techniques.

In chapter 3, the mathematical background required for modelling a D2D communication system, including the effects of multipath propagation shortcomings, was discussed. Based on the variation of the received signal strength, impairments can be categorized into two groups of large and small-scale impairments. Large-scale effects happen over large distances or during long time intervals (compared with the carrier frequency), and small-scale effects take place over small distances or short time intervals. Impairments such as path loss, noise, shadowing, and fading were covered. Moreover, the use of multiple antenna systems for overcoming fading degradation and combating interference effects was discussed.

An underlay of D2D communications that share the UL spectrum of a cellular network is investigated in chapter 4. A careful power control mechanism is a requirement for underlay D2D communication systems to control the level of interference, and thus to obtain the desired spectral efficiencies. We derived formulas to calculate the minimum amount of transmission power for both CUEs and DUEs to achieve such goals. We further use the concept of massive MIMO to minimise the interference effects of the user-to-cellular links.

A cellular vehicular communication system is discussed in chapter 5 that uses the concept of D2D communication for establishing V2V links. Therefore, nearby vehicles would be able to communicate with one another without their data traversing the core network. Furthermore, the V2I links were modelled by Device-to-eNodeB communication links. The formulas that were derived in the previous chapter have been expanded for this model, which resulted in equations to calculate the minimum transmission power for achieving the required spectral efficiencies of both V2I and V2V links.

To demonstrate the effect of transmission power on the spectral efficiencies of V2I and V2V links, we perform numerical analysis in chapter 6. Simulations are done based on 3GPP TR 36.885 parameters. It was shown that to maintain the required level of QoS, the transmission power should be increased as the number of V2V links increases. Furthermore, obtaining a higher $R_0^{(\mathrm{V2I})}$ requires spending more power for transmission. We also showed that the QoS of

V2V links degrades by increasing the number of V2V links. This is as a result of the additional interferences, which are introduced to the system by each extra V2V communication link.

In summary, cellular-based vehicular communication can pave the way for designing highly efficient and cost-effective driver assistance systems based on collaborative and remote processing solutions. The main transmission links for vehicular communication systems are V2V and V2I. D2D communication links are considered for establishing V2V links, and cellular communication links are employed for V2I links. An underlay in-band D2D communication is considered, where DUE's reuse the cellular UL spectrum. Statistical methods are employed to find boundaries on the allocated transmission powers for achieving sufficient spectral efficiencies in V2I and V2V links without considering any prior knowledge on vehicles' locations or the channel state information. The capacity of such a system is directly proportional to the energy of a transmitted signal, and in fact, achieving the desired level of QoS requires careful control of transmission power for all the radio sources within a system.

In this research, we only consider devices with a single antenna. Therefore, as future work, systems with multiple-antennas devices can be considered. The other assumption that has been made with regards to employing massive MIMO was considering favourable propagation. However, this may not be held when we have a channel with correlated scatters. This topic can also be considered in future research.

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